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A Hybrid Multi-Sensor Monitoring Framework for Spatial Screening of Particulate and Gaseous Pollutants around a Tropical Urban Landfill

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ABSTRACT

Open landfills generate complex mixtures of particulate and gaseous pollutants that can affect nearby communities. However, distance alone does not adequately explain their short-term spatial distribution. This study characterized multiple air pollutants surrounding the Tamangapa Landfill in Indonesia, compared concentrations between near and outer zones, and examined their relationships with distance and meteorological conditions. Field observations were conducted at nine locations situated 200–640 m from a central reference point. PM_{1.0}, PM_{2.5}, PM₁₀, formaldehyde, total volatile organic compounds (TVOC), CO, CO₂, CH₄, H₂S, O₂, and the lower explosive limit (LEL) were measured using complementary portable sensors. Analytical methods included descriptive statistics, Mann–Whitney tests, Cliff’s delta, Spearman correlations, and Benjamini–Hochberg corrections. Particulate concentrations exhibited substantial spatial heterogeneity, with maximum PM_{1.0}, PM_{2.5}, and PM₁₀ concentrations of 146, 242, and 272 µg/m³, respectively. Mean

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ARTICLE INFO

Received: 23 August 2026 | Revised: 23 September 2026 | Accepted: 30 September 2026 | Published Online: 9 October 2026
DOI: <https://doi.org/10.30564/re.v8i5.13920>

CITATION

Yunus, S., Marzuki, I., Hasnawi, M., et al., 2026. A Hybrid Multi-Sensor Monitoring Framework for Spatial Screening of Particulate and Gaseous Pollutants around a Tropical Urban Landfill. *Research in Ecology*. 8(5): 156–174. DOI: <https://doi.org/10.30564/re.v8i5.13920>

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concentrations in the near zone were approximately 3.6–3.7 times higher than those in the outer zone. TVOC showed a strong negative correlation with distance ($r_s = -0.812$; $p = 0.0079$), although this association did not remain statistically significant after correction for multiple testing ($q = 0.063$). Pollutant distributions appeared to reflect interactions among distance, plume orientation, meteorological conditions, measurement time, and local activities. This study introduces a hybrid multi-sensor screening framework that integrates particulate, gaseous, spatial, and meteorological measurements for tropical landfill environments, particularly in resource-limited settings where conventional monitoring networks remain limited.

Keywords: Particulate Matter; Formaldehyde; Total Volatile Organic Compounds; Open Landfill; Portable Air-Quality Sensor

1. Introduction

Global municipal solid waste generation continues to increase, posing significant environmental and public health challenges. This burden is particularly acute in developing countries, where rapid population growth, urbanization, and changing consumption patterns have intensified waste generation and overwhelmed existing waste-management systems. However, the infrastructure required for waste treatment, including suitable disposal facilities and specialized equipment, has often failed to keep pace with these changes^[1,2]. According to estimates in the *Global Waste Management Outlook 2024*, global municipal solid waste generation is projected to increase from approximately 2.1 billion tonnes in 2023 to 3.8 billion tonnes in 2050. More concerning, regions where waste volumes are growing most rapidly still rely primarily on primitive disposal methods, including open dumping and uncontrolled incineration. If this trend continues, surrounding air quality may deteriorate further, greenhouse gas emissions may continue to increase, fragile ecosystems may suffer irreversible damage, and public health expenditures may rise^[3]. This challenge is especially pronounced in tropical urban settings, where consistently high temperatures, elevated relative humidity, and intense solar radiation accelerate the anaerobic decomposition of organic waste, enhance the volatilization of organic compounds, and modify atmospheric mixing processes. These climate-driven changes ultimately affect both the emission strength of landfill sources and the dispersion, transformation, and deposition patterns of airborne pollutants in surrounding communities^[4,5].

Landfills that rely on open disposal are complex emission sources because they receive mixtures of organic and inorganic materials with diverse physical and chemical prop-

erties^[6]. Anaerobic decomposition of organic matter produces landfill gases consisting mainly of methane and carbon dioxide, along with lower concentrations of hydrogen sulfide, ammonia, carbon monoxide, and various volatile organic compounds (VOCs). At the same time, waste unloading, compaction, transport-vehicle movement, surface erosion, dust resuspension, and open combustion can release particulate matter into the atmosphere. The interaction of these processes exposes the surrounding environment to particulate mixtures, decomposition products, vehicle emissions, incomplete-combustion products, and secondary aerosols^[7,8]. Open waste burning can also cause short-term surges in particulate-matter concentrations in nearby residential areas^[9]. Particulate-matter concentrations around landfills are not determined solely by continuous landfill emissions. Activities such as waste burning, waste disposal, demolition operations, and repeated movements of operational vehicles are intermittent and do not occur continuously every day or at the same locations. Even when such activities occur only briefly, particulate-matter concentrations in the surrounding air can increase sharply, producing pronounced short-term peaks.

Fine particulate matter suspended in the air poses serious risks to human health, as has been extensively documented. The location at which inhaled particles are deposited in the human body is closely related to their aerodynamic diameter. This parameter reflects not only particle size but also particle density and movement characteristics in air^[9]. PM₁₀ has an aerodynamic diameter of no more than 10 μm , enabling it to enter the respiratory tract and deposit in the nasopharyngeal and tracheobronchial regions. PM_{2.5} has an aerodynamic diameter of no more than 2.5 μm , allowing it to penetrate more deeply into the respiratory tract and reach the

alveolar region^[9]. PM_{1.0} has an aerodynamic diameter of no more than 1 µm and is therefore useful for characterizing the finer fraction of airborne particulate matter. These very small particles can remain suspended for extended periods and penetrate deeply into the respiratory system^[10].

Epidemiological studies have demonstrated that exposure to airborne particulate matter is associated with systemic inflammation, oxidative stress, reduced lung function, cardiovascular disease, chronic obstructive pulmonary disease, lung cancer, and increased overall mortality risk^[11–13]. Based on this body of evidence, the World Health Organization established 24-h guideline values for PM_{2.5} and PM₁₀ of 15 and 45 µg/m³, respectively. These guideline values are defined according to specific averaging periods; therefore, single-moment or one-hour measurements cannot formally determine whether a location complies with these values.

In addition to particulate matter, landfills may release a wide range of VOCs through material evaporation, biological degradation, chemical reactions, vehicle emissions, and incomplete combustion. Real-time VOC measurements at closed landfills further indicate that VOC composition and flux can vary according to season, temperature, atmospheric pressure, and landfill-management characteristics^[14]. Formaldehyde (HCHO) is a volatile carbonyl compound of concern because short-term exposure may cause eye and respiratory irritation, whereas long-term exposure is associated with carcinogenic risk^[13]. The WHO guideline value for formaldehyde is 0.1 mg/m³ over a 30-min averaging period. However, HCHO results obtained using portable sensors must be interpreted cautiously because sensor responses can be affected by detection limits, humidity, temperature, calibration, and cross-sensitivity to other compounds^[15]. Interpretation of total volatile organic compounds (TVOC) also has limitations. TVOC represents the combined instrument response to a mixture of VOCs but does not indicate the identity, proportion, toxicity, or reactivity of individual compounds^[16,17]. Two sites with identical TVOC values may have different chemical compositions and health risks. Therefore, TVOC is more appropriately used as an initial screening indicator of mixtures of organic emissions. Identification of individual compounds requires sorbent-tube or specialized-container sampling followed by gas chromatography–mass spectrometry analysis^[17].

The distribution of pollutants around landfills is not determined solely by distance from the source. Wind direction determines the transport pathway of air masses, whereas wind speed may either enhance dilution or transport pollutant plumes from the source toward monitoring instruments. Temperature can affect decomposition rates and the volatility of organic compounds, while humidity can influence particle hygroscopic growth and optical-sensor responses. Low-cost optical sensors can be particularly sensitive to relative humidity and may produce biased measurements under humid conditions, potentially resulting in systematic overestimation or underestimation of particulate concentrations. To address this limitation, machine-learning-based classification and regression models have been developed and validated as potential approaches for correcting sensor bias during field deployment.

Measurement time, atmospheric stability, local morphology, buildings, vegetation, waste-unloading volume, vehicle density, and combustion activity may also contribute to variations among locations and measurement periods. Consequently, locations close to a landfill do not necessarily exhibit the highest pollutant concentrations if they are positioned upwind, whereas more distant locations may exhibit higher concentrations if they lie along a plume pathway. Portable sensors offer advantages in terms of mobility, spatial resolution, operational simplicity, and the ability to identify locations with relatively high pollutant concentrations. However, portable sensors vary in data quality and are not automatically equivalent to reference methods. Responses from light-scattering PM sensors can be affected by particle size, shape, density, refractive index, composition, and water content. Therefore, collocation with reference instruments, calibration documentation, functional checks, and data-quality control are important components of sensor-based studies^[18]. In addition to machine-learning approaches, conventional statistical correction methods have been developed to improve the accuracy of low-cost sensor networks. These methods require collocated data from reference-grade instruments and adjust raw sensor readings using regression-based or bias-correction algorithms. Such approaches can reduce systematic errors and improve the reliability of spatially distributed monitoring networks^[19]. This context is particularly relevant to the Tamangapa Final Disposal Site, the main municipal solid-waste disposal facility in Makassar City, which

borders residential areas and supports various community activities. Previous studies have shown that the Tamangapa Landfill is operating beyond capacity and continues to use an open-disposal system, resulting in substantial interactions among waste piles, landfill operations, and the surrounding environment^[20].

Many local studies have focused on waste pickers working at landfills and have examined methane production potential, ammonia concentrations, hydrogen sulfide exposure, and respiratory symptoms^[21–23]. However, these studies have several limitations. Most have analyzed only a single type of gas or have focused primarily on health effects among workers without integrating multiple environmental dimensions. Specifically for the Tamangapa Landfill, observational data combining multiple particulate-size fractions, HCHO, TVOC, auxiliary monitoring gases, and local meteorological conditions at multiple surrounding locations remain limited. Furthermore, few studies have examined whether variation in pollutant concentrations at different locations around tropical open-air landfills can be explained adequately by geographic distance alone.

This study had three primary objectives: first, to characterize short-term variation in PM_{1.0}, PM_{2.5}, PM₁₀, HCHO, and TVOC at nine monitoring points around the Tamangapa Landfill; second, to compare concentrations between near and outer zones; and third, to explore correlations among pollutant concentrations, distance from the landfill reference point, and meteorological conditions. CO, CO₂, CH₄, H₂S, O₂, and the lower explosive limit (LEL) were used as auxiliary parameters to support the analysis of the core pollutants. The primary contribution of this study lies in its simultaneous consideration of multiple pollutants and its demonstration that short-term pollutant concentrations around landfills reflect the combined influence of multiple factors, including pollution sources, atmospheric dispersion processes, characteristics of the surrounding area, measurement time, and local human activities, rather than geographic distance alone.

2. Materials and Methods

2.1. Research Design

This study used a field observational design combined with spatial comparison methods. All observations were conducted on-site, and data collected from different loca-

tions were subsequently compared. Between April and July 2026, measurements were conducted at nine sampling points around the Tamangapa Landfill in Makassar City. Each sampling point was monitored once, with no repeated measurements, and each monitoring session lasted exactly 60 min. All measurements were conducted between 08:20 and 18:20 Central Indonesian Time (WITA), covering morning, midday, afternoon, and evening periods. This measurement window was not intended to generate daily, seasonal, or annual averages but rather to identify short-term differences in pollutant concentrations among sampling points and to describe spatial variations within the limited measurement period.

Monitoring could not be conducted simultaneously at all sampling points. Measurements were therefore performed sequentially, making it impossible to record values from all locations at exactly the same time. Consequently, the observed differences reflected the combined effects of spatial differences among sampling points, time lags resulting from sequential measurements, meteorological conditions, landfill operational status, and local pollutant-emission sources. These factors could not be fully separated, and this limitation is discussed comprehensively in Section 5. Accordingly, this study was not designed to establish a causal relationship between distance from the landfill and pollutant concentration, nor does it support causal conclusions such as “the closer a location is to the landfill, the higher the pollutant concentration.” The portable monitoring instruments and field configuration are shown in **Figure 1**.

2.2. Location and Measurement Points

This study was conducted around the Tamangapa Landfill, a major municipal solid-waste disposal facility in Makassar, South Sulawesi, Indonesia. The surrounding area includes mixed land uses, including residential areas, roads, farmland, vegetation, and commercial activities. Measured pollutant concentrations may therefore reflect both landfill operations and other local sources, including traffic, waste-collection vehicles, residential activities, biomass burning, and resuspended dust, thereby limiting definitive source attribution.

Spatial distances were calculated from Point 0, a fixed reference point within the landfill boundary that was used solely as a spatial anchor and not as a sampling location or as the presumed origin of all landfill emissions. In addition

to Point 0, nine sampling points were established in the surrounding area, with distances from Point 0 ranging from 200 to 640 m. Their locations are shown in **Figure 2**. Two main principles guided the selection of sampling points: coverage

of multiple geographic orientations around the landfill and compliance with operational field requirements, including accessibility, safety, land-use compatibility, and sufficient space for equipment.

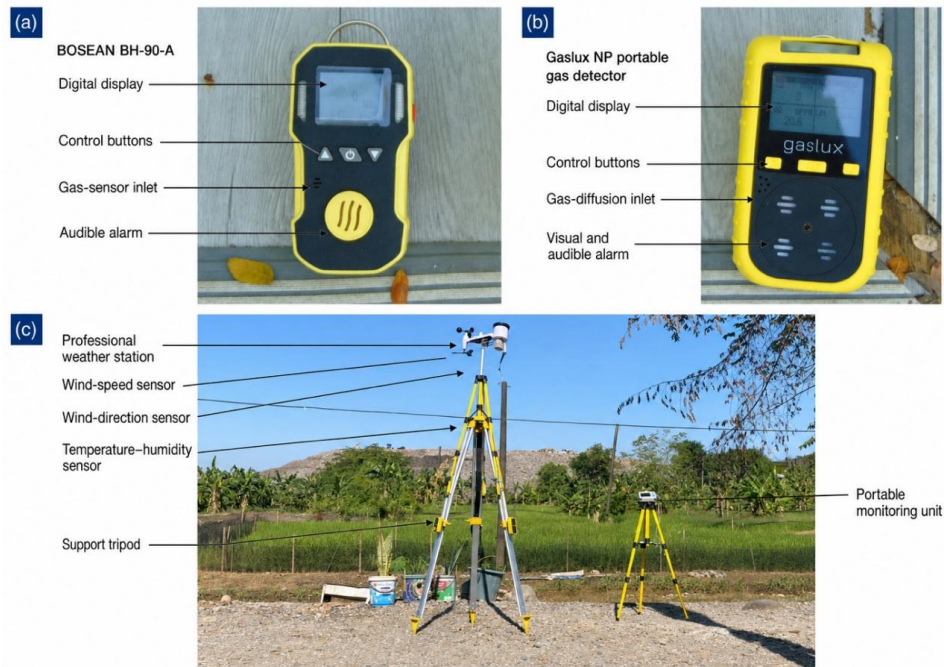


Figure 1. Portable monitoring instruments and field configuration used during air-quality measurements around the Tamangapa Landfill: (a) BOSEAN BH-90-A portable gas detector, (b) Gaslux NP portable gas detector, and (c) professional weather station with portable monitoring unit.



Figure 2. Location of the Tamangapa Landfill and distribution of nine air-quality measurement points.

The nine measurement locations were operationally classified into near and outer zones according to their distance from Point 0. The near zone consisted of four locations situated 200–375 m from the reference point: Points 1, 7, 8, and 9. The outer zone consisted of five locations situated

415–640 m from the reference point: Points 2, 3, 4, 5, and 6. This separation was based on the observed distribution of distances because no measurement locations were situated between 375 and 415 m as seen in **Table 1**. This classification was developed solely for exploratory spatial analysis. It

was not intended to establish administrative boundaries, regulatory buffer zones, exposure boundaries, or health-based setback distances. Classification within the near zone does not necessarily indicate greater landfill-related exposure, nor

does classification within the outer zone indicate an absence of landfill influence. Geographic distance was treated as one potential explanatory variable rather than as the sole determinant of pollutant concentration.

Table 1. Measurement point characteristics.

Point	Distance from Point 0 (m)	Operational Zone	Measurement Time (WITA)	Wind Direction of Origin	Wind Speed (km/h)
1	340	Near	17:20–18:20	Northwest	0.3
2	415	Outer	08:20–09:20	South	3.6
3	500	Outer	17:20–18:20	South	6.1
4	640	Outer	13:20–14:20	West	0.4
5	475	Outer	14:30–15:30	South	1.3
6	570	Outer	09:20–10:20	Southeast	2.5
7	270	Near	09:50–10:50	Southeast	8.6
8	200	Near	14:15–15:15	Southwest	5.5
9	375	Near	16:15–17:15	Southeast	3.6

Note: WITA refers to Central Indonesian Time (UTC + 8). Wind direction is defined as the direction from which the wind originates.

Land-use information for each point was obtained from field records and on-site observations. However, variables such as proximity to roads, vegetation cover, building density, ongoing waste-treatment activities, and other local emission sources were not recorded using a standardized classification system. In addition, distances were calculated from Point 0 rather than from the landfill boundary or individual emission zones. These site characteristics therefore served only as contextual information and were not included as quantifiable explanatory variables in subsequent analyses. The core analyzable data, including distance, measurement time, pollutant concentrations, and meteorological conditions, were extracted from the corresponding field records.

Wind direction was recorded according to its direction of origin. For example, a southeast wind indicates that the air mass moves from southeast to northwest. Points 1 and 4 recorded very low wind speeds of 0.3 and 0.4 km/h, respectively. Under near-calm conditions, wind-direction measurements may become unstable and may not reliably represent the dominant pollutant-transport pathway. In contrast, Point 7 recorded a wind speed of 8.6 km/h, the highest observed during the study. Higher wind speeds may enhance dilution; however, if a monitoring point lies directly within a pollutant plume, stronger winds may also transport pollutant-rich air toward the monitoring equipment and result in elevated measured concentrations.

Monitoring points were not formally classified as upwind, crosswind, or downwind. First, some coordinates in the original field records require verification. Second,

monitoring was not conducted simultaneously; therefore, wind direction and other meteorological conditions may have changed among monitoring periods, altering the position of each point relative to the pollutant plume. A point that was downwind during one measurement period could have occupied a different relative position several hours later. Therefore, wind direction was used only as contextual information to assist in interpreting pollutant transport and dispersion and not as definitive evidence that measured pollutants originated from the landfill.

Each monitoring point was measured once for 60 consecutive minutes. Measurement periods differed among locations, with some observations conducted in the morning and others in the afternoon or evening. Differences in pollutant concentrations among locations therefore cannot be attributed to a single factor. Instead, they reflect the combined effects of spatial location, sequential measurement times, meteorological conditions, changes in landfill operations, and potentially other local emission sources. Consequently, this design allows only preliminary screening of short-term spatial differences.

2.3. Parameters and Instruments

The main study parameters were PM_{1.0}, PM_{2.5}, PM₁₀, formaldehyde, and TVOC. Supporting parameters included CO, CO₂, CH₄, H₂S, O₂, and LEL. Recorded micrometeorological conditions included air temperature, relative humidity, wind direction, and wind speed. Pollutant measurements

were conducted using the TC-700PRO Multiple Air Quality Detector, BOSEAN BH-90-A Portable Single Gas Detector, and Gaslux NP Portable Gas Detector. Based on the instrument output channels, $PM_{1.0}$, $PM_{2.5}$, and PM_{10} were reported in $\mu g/m^3$; HCHO and TVOC in mg/m^3 ; CO, CO_2 , and H_2S in ppm; O_2 as volume percent; and CH_4 and LEL according to the units displayed by the instruments. Particulate matter was measured using the laser-scattering principle. Formaldehyde and TVOC data were collected using metal-oxide semiconductor sensors, whereas CO_2 was measured using non-dispersive infrared detection.

Key parameters for each measurement channel, including measurable range, minimum distinguishable change, lowest detectable value, manufacturer-specified accuracy, response time, and potential interferents, are documented in the instrument specification sheets or additional materials.

On-site meteorological conditions were monitored using a professional weather station that continuously recorded air temperature, relative humidity, wind direction, and wind speed. All wind-direction measurements were calibrated relative to true north. The meteorological station was operated in accordance with internationally accepted guidance covering sensor calibration, installation, measurement frequency, and data-quality control. Adherence to these procedures was intended to support the accuracy and comparability of the recorded air temperature, relative humidity, wind direction, and wind speed data used to interpret pollutant-dispersion patterns around the landfill^[24].

The portable sensors used in this study were treated as preliminary screening-level monitoring instruments. They were not intended to generate regulatory-grade data or to serve as reference instruments approved by regulatory authorities because supporting validation data from collocation with standard reference methods were not available. U.S. EPA guidance emphasizes that several key considerations should be aligned with the intended data-quality level, including intended data use, equipment specifications, calibration status, collocation status, installation location, and quality-control procedures throughout the monitoring process^[25].

2.4. Measurement Procedure

Before each measurement, the instruments were switched on and allowed to warm up for 30–60 min until their responses stabilized. Initial checks included battery

status, zero or fresh-air zero checks, sensor functionality, and instrument time synchronization. For portable gas detectors, a functional check or bump test was performed according to the manufacturer's instructions, consistent with OSHA recommendations for exposing instruments to known concentrations of standard gases to verify sensor response^[26]. The instruments were positioned approximately 2–2.5 m above ground level and away from physical barriers, waste surfaces, vehicle exhaust, and artificial airflow. Continuous measurements were conducted for 60 min at each location. The concentration reported for each pollutant at each monitoring location represented the average of all valid readings collected during the full 60-min monitoring period rather than the final value displayed by the instrument. Before calculating the averages, recorded data were checked and missing, negative, and out-of-range readings were excluded. During each measurement session, information on sampling time, distance, wind direction, wind speed, air temperature, relative humidity, and general site conditions was recorded. However, traffic intensity, waste unloading, open burning, dust resuspension, and other local emission activities were not systematically quantified and were therefore considered potential sources of uncertainty.

2.5. Quality Assurance and Control

Quality-control procedures included checks of measurement units, measurement duration, point identity, value ranges, and data transcription. Before analysis, sensor readings were checked for negative values, missing data, and unchanged readings. Two major transcription errors were identified during the dataset audit: a CO_2 value for Point 3 (5 ppm $\rightarrow$ 380 ppm) and a TVOC value for Point 6 (0.007 $\rightarrow$ 0.0007 mg/m^3). The audit trail recorded the pre- and post-correction values, reasons for correction, correction dates, and supporting source evidence. All analyses were conducted using the corrected values.

The reporting resolution of the instruments did not permit reliable differentiation between very low concentrations and complete absence of CH_4 and H_2S . Therefore, zero readings for these compounds were interpreted as “not detected” rather than as evidence that the compounds were absent from ambient air. The LEL reading was not interpreted as a methane concentration because LEL represents an instrument response relative to the calibration gas and

target properties of the flammable-gas sensor. Before each measurement, instrument battery status and sensor performance were checked, time synchronization was verified, and stable readings were confirmed after a 30–60-min warm-up period. Because no collocation with reference monitors was conducted, all results were considered screening-level measurements.

2.6. Data Analysis

Data analysis was conducted using R software version 4.6.1. For each parameter, mean, median, standard deviation, minimum, maximum, range, and coefficient of variation were calculated. The coefficient of variation was calculated as:

$$CV = (SD/\bar{x}) \times 100$$

The descriptive comparison between near and outer zones was expressed using the average ratio:

$$R = \bar{x}_{near}/\bar{x}_{outer}$$

PM_{2.5}/PM₁₀ and PM_{1.0}/PM_{2.5} ratios were calculated at each point to illustrate the relative contribution of finer particulate fractions. These size ratios were not used as definitive source-identification indicators. Differences between zones were evaluated using an exact two-sided Mann–Whitney test, which uses an exact permutation distribution and does not rely on large-sample asymptotic assumptions. Cliff's delta was used to quantify the magnitude and direction of differences between zones and is suitable for small and non-normally distributed samples. A positive value indicates that concentrations tended to be higher in the near zone.

Relationships between distance and pollutant concentrations were evaluated using Spearman's rank correlation. Correlations between pollutant concentrations and wind speed, temperature, and relative humidity were also examined as exploratory analyses. Because multiple correlations were tested, p-values were adjusted using the Benjamini–Hochberg procedure to control the false-discovery rate. A leave-one-out sensitivity analysis was performed by removing each monitoring location in turn and recalculating the correlation coefficients. Statistical significance was not treated as the sole criterion for interpretation. The analysis considered effect sizes, concentration levels, confidence intervals, data distributions, and overall patterns, as well as the direction and strength of correlations, spatial consistency, and

theoretical plausibility. Single 60-min measurements were not used to assess regulatory compliance because the applicable guideline values are based on longer averaging periods. Comparisons with WHO guideline values were therefore provided only for contextual purposes.

3. Results and Discussion

3.1. Meteorological Conditions

During the measurement period, air temperature ranged from 29.0 to 33.6 °C, with a mean of 31.47 ± 1.99 °C. Relative humidity ranged from 50.93% to 65.50%, with a mean of 58.34 ± 5.73%. Wind speeds ranged from 0.3 to 8.6 km/h, equivalent to approximately 0.08–2.39 m/s. The main recorded wind directions were northwest, south, west, southeast, and southwest.

The near zone had a mean air temperature of 31.68 °C, relative humidity of 58.39%, and wind speed of 4.50 km/h. The outer zone had a mean air temperature of 31.30 °C, relative humidity of 58.29%, and wind speed of 2.78 km/h. Mean temperature and relative humidity differed only slightly between the two zones. However, wind direction, wind speed, and measurement time varied among individual monitoring points. Thus, the observed differences in pollutant concentrations cannot be explained solely by zone classification.

Points 1 and 4 experienced near-calm conditions, with wind speeds of 0.3 and 0.4 km/h, respectively. Under such low wind speeds, wind direction may become unstable and difficult for instruments to resolve reliably. Point 7 recorded a wind speed of 8.6 km/h, the highest observed during the study. At some locations, nearly stagnant air may have promoted local pollutant accumulation, whereas stronger air circulation at other locations may have enhanced dispersion. Under weak-wind conditions, pollutants may accumulate near their sources and disperse slowly. At higher wind speeds, pollutants may either be diluted more rapidly or transported preferentially toward a particular receptor, depending on plume orientation and source activity.

The pollutant concentration measured at each monitoring location therefore reflected the environmental conditions at that location and during that specific measurement period. The measurements did not represent synchronous observations obtained under identical atmospheric conditions.

More importantly, monitoring at all points was conducted sequentially, with substantial differences in measurement time among locations.

Consequently, concentration differences among locations cannot be interpreted simply as fixed spatial differences. They also incorporate variability associated with temporal and environmental changes among measurement periods. Each measurement therefore reflected the combined influence of location, time of day, wind conditions, landfill operational status, and human activities. Spatial location was

only one of several influencing factors. Accordingly, the spatial patterns described in this study should be regarded as exploratory short-term observations rather than evidence of a stable pollutant-concentration gradient around the landfill.

3.2. Descriptive Statistics of Pollutants

The measurement results showed substantial spatial heterogeneity, particularly for particulate matter and CO. **Table 2** summarizes the descriptive statistics for the principal air-quality parameters.

Table 2. Descriptive statistics of air-quality parameters.

Parameter	Mean $\pm$ SD	Median	Min–Max	CV (%)	Highest Point
PM _{1.0} ($\mu\text{g}/\text{m}^3$)	48.44 $\pm$ 50.55	20	9–146	104.35	Point 9
PM _{2.5} ($\mu\text{g}/\text{m}^3$)	74.22 $\pm$ 79.49	28	12–242	107.10	Point 9
PM ₁₀ ($\mu\text{g}/\text{m}^3$)	81.33 $\pm$ 88.15	31	14–272	108.38	Point 9
HCHO ($\mu\text{g}/\text{m}^3$)	2.00 $\pm$ 1.00	2.00	1.00–4.00	50.00	Point 1
TVOC ($\mu\text{g}/\text{m}^3$)	0.66 $\pm$ 0.25	0.60	0.30–1.10	38.22	Point 8
CO (ppm)	11.33 $\pm$ 15.44	5	0–43	136.19	Point 7
CO ₂ (ppm)	562.78 $\pm$ 83.48	565	380–699	14.83	Point 4
LEL (%LEL)	5.78 $\pm$ 2.22	5	3–11	38.49	Point 6

Note: CV = coefficient of variation.

The coefficient of variation represents the degree of variability relative to the mean. PM_{1.0}, PM_{2.5}, and PM₁₀ all had CV values exceeding 100%, indicating substantial variability across measurement locations. This high variability was largely influenced by a small number of locations with significantly elevated concentrations. Among all measured parameters, CO showed the greatest relative variability (CV = 136.19%), whereas CO₂ was comparatively stable (CV = 14.83%). The significant heterogeneity in pollutant concentrations across locations is consistent with the characteristics of landfill-related and local emission sources, which may be spatially dispersed, intermittently active, and subject to nonuniform atmospheric transport. Waste transfer and treatment activities, vehicle movements, road-dust resuspension, local combustion, and movement of polluted air masses may all contribute to short-term concentration peaks.

3.3. Variations in PM_{1.0}, PM_{2.5}, and PM₁₀

The three measured particulate fractions exhibited substantial variation across the monitoring locations and did not show a simple monotonic relationship with distance from Point 0 (**Figure 3**). Point 9, located 375 m from Point 0, recorded the highest concentrations of all three particulate fractions: 146 $\mu\text{g}/\text{m}^3$ for PM_{1.0}, 242 $\mu\text{g}/\text{m}^3$ for PM_{2.5}, and

272 $\mu\text{g}/\text{m}^3$ for PM₁₀. Point 7, located 270 m from Point 0, recorded the second-highest particulate concentrations. In contrast, Point 8, the closest monitoring location to Point 0 at a distance of 200 m, recorded the lowest particulate concentrations, with values of 9 $\mu\text{g}/\text{m}^3$ for PM_{1.0}, 12 $\mu\text{g}/\text{m}^3$ for PM_{2.5}, and 14 $\mu\text{g}/\text{m}^3$ for PM₁₀. Point 6, located 570 m from Point 0, also exhibited relatively low particulate concentrations. These observations indicate that particulate-matter concentrations did not decrease consistently with increasing distance from Point 0.

The high particulate concentrations observed at Points 7 and 9 may have been related to plume position, waste-management activities, vehicular traffic, dust resuspension, or local combustion. However, because the intensities of these activities were not quantitatively recorded, their individual contributions could not be distinguished. The low particulate concentrations at Point 8, despite its proximity to Point 0, may have occurred because the location was outside the plume pathway during measurement or because prevailing wind conditions promoted pollutant dilution. Of the nine 60-min PM_{2.5} measurements, seven were numerically higher than the WHO 24-h guideline value of 15 $\mu\text{g}/\text{m}^3$. Similarly, four of the nine PM₁₀ measurements were numerically higher than the corresponding 24-h guideline value of 45 $\mu\text{g}/\text{m}^3$. However, these comparisons cannot be interpreted as evi-

dence of guideline exceedance. The measurements in this study represent 60-min averages, whereas WHO guideline values are based on 24-h averages. Because the averaging periods differ substantially, the measurements cannot be used directly to determine regulatory or guideline compliance.

Nevertheless, the observed short-term elevations remain relevant for screening purposes. Locations at which high short-term particulate concentrations were observed may warrant priority for follow-up monitoring using repeated or continuous measurements.

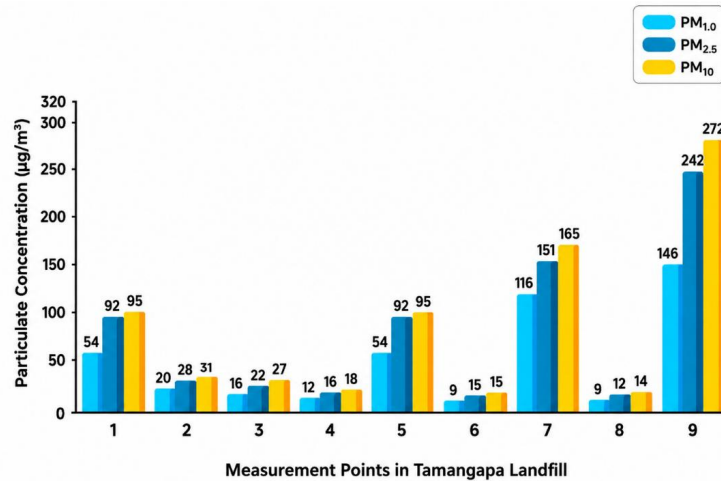


Figure 3. Concentrations of PM_{1.0}, PM_{2.5}, and PM₁₀ at nine measurement points.

3.4. Particulate-Fraction Ratios

PM_{2.5}/PM₁₀ ratios ranged from 0.815 to 0.968, with a mean of 0.897. Thus, on average, approximately 89.7% of

the measured PM₁₀ mass consisted of PM_{2.5}, leaving approximately 10% attributable to the coarse particulate fraction of 2.5–10 µm. PM_{1.0}/PM_{2.5} ratios ranged from 0.587 to 0.768, with a mean of 0.687 as represented in **Table 3**.

Table 3. Ratio of particulate fractions.

Point	PM _{2.5} /PM ₁₀	PM _{1.0} /PM _{2.5}
1	0.968	0.587
2	0.903	0.714
3	0.815	0.727
4	0.889	0.750
5	0.968	0.587
6	0.867	0.692
7	0.915	0.768
8	0.857	0.750
9	0.890	0.603

The predominance of PM_{2.5} within PM₁₀ may be associated with fine-particle emissions from combustion sources, motor-vehicle exhaust, secondary aerosol formation, and waste-treatment processes. However, particle-size ratios alone cannot definitively identify emission sources or confirm their locations. Reliable source identification would require additional chemical characterization, including analysis of organic carbon, elemental carbon, ions, metals, and organic compounds. An additional limitation is that the optical instrument used the same underlying particle-size distribution model and estimation algorithm to calculate the different par-

ticulate fractions rather than measuring each fraction independently. Consequently, strong correlations among particle-size fractions may reflect both genuine relationships in source characteristics and atmospheric transport and artifacts arising from the instrument's shared estimation algorithm.

3.5. Comparison between Near and Outer Zones

Mean PM_{1.0} concentration in the near zone was 81.25 µg/m³ compared with 22.20 µg/m³ in the outer zone, cor-

responding to a near-to-outer ratio of approximately 3.66. PM_{2.5} showed a similar pattern, with a mean concentration of 124.25 µg/m³ in the near zone and 34.20 µg/m³ in the outer zone, corresponding to a ratio of 3.63. For PM₁₀, the mean concentration was 136.50 µg/m³ in the near zone and 37.20 µg/m³ in the outer zone, corresponding to a ratio of

3.67. Mean concentrations of HCHO, TVOC, and CO were also higher in the near zone than in the outer zone. Among these parameters, TVOC showed the most pronounced and consistent zonal difference, with mean values of 0.85 µg/m³ in the near zone and 0.50 µg/m³ in the outer zone as seen in **Table 4**.

Table 4. Comparison between near and outer zones.

Parameter	Near Zone, Mean ± SD	Outer Zone, Mean ± SD	Near/Outer Ratio	95% CI for Ratio	Mann–Whitney <i>p</i>	Cliff's δ	Effect Size
PM _{1.0} (µg/m ³)	81.25 ± 61.54	22.20 ± 18.25	3.66	0.82–16.3	0.286	0.50	Medium
PM _{2.5} (µg/m ³)	124.25 ± 96.99	34.20 ± 32.82	3.63	0.76–17.4	0.413	0.45	Medium
PM ₁₀ (µg/m ³)	136.50 ± 109.39	37.20 ± 32.96	3.67	0.74–18.2	0.413	0.45	Medium
HCHO (µg/m ³)	2.50 ± 1.29	1.60 ± 0.55	1.56	0.68–3.58	0.413	0.45	Medium
TVOC (µg/m ³)	0.85 ± 0.21	0.50 ± 0.16	1.70	1.02–2.83	0.063	0.85	Large
CO (ppm)	16.75 ± 18.39	7.00 ± 13.04	2.39	0.53–10.8	0.413	0.45	Medium
CO ₂ (ppm)	569.25 ± 27.02	557.60 ± 115.39	1.02	0.81–1.28	1.000	0.00	Negligible
LEL (%LEL)	5.75 ± 0.96	5.80 ± 3.03	0.99	0.53–1.85	0.556	0.30	Small

Although mean concentrations of most pollutants were higher in the near zone, none of the differences reached conventional statistical significance. This lack of statistical significance should be interpreted in the context of the small and unbalanced groups, comprising four near-zone and five outer-zone locations, as well as substantial within-zone variability. In addition, the monitoring points were not measured simultaneously, and meteorological and landfill-operational conditions differed among measurement sessions. The concentration ratios and Cliff's delta values should therefore be interpreted as preliminary indicators of spatial differences rather than as estimates of the additional pollution attributable specifically to the landfill.

Among the monitored pollutants, TVOC exhibited the

largest effect size (Cliff's $\delta = 0.85$). Nevertheless, this finding requires confirmation through adequately replicated consecutive measurements, simultaneous monitoring across locations, and the inclusion of appropriate upwind or background controls. Mean PM_{1.0}, PM_{2.5}, and PM₁₀ concentrations in the near zone were approximately 3.6–3.7 times higher than those in the outer zone as illustrated in **Figure 4**. However, these differences were not statistically significant. Consequently, the observed elevation in near-zone particulate concentrations should be interpreted as a preliminary spatial pattern rather than as direct evidence that landfill-related particulate pollution decreases with increasing distance. Statistical power was limited by the small number of monitoring points and high within-zone variability.

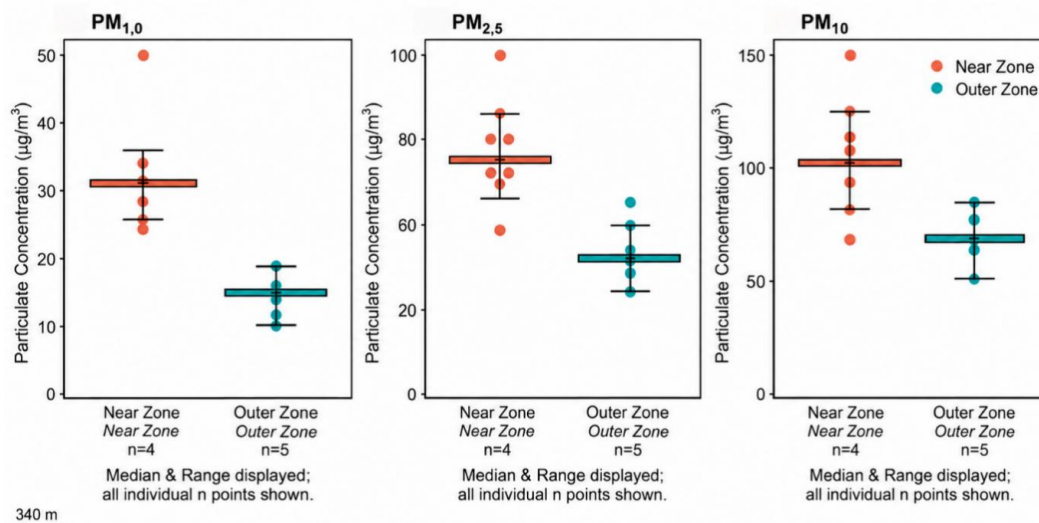


Figure 4. Distribution of PM_{1.0}, PM_{2.5}, and PM₁₀ in near and outer zones of the landfill.

Near-zone mean concentrations were strongly influenced by the high values recorded at Points 7 and 9 and the low values recorded at Point 8. Therefore, individual monitoring-point data should be considered alongside group averages. Bar charts or summary statistics based solely on mean values may obscure substantial variability among individual locations.

3.6. Relationship between Distance and Pollutant Concentration

Most pollutants showed nominally negative correlations with distance. Before correction for multiple testing, only TVOC had a p -value below 0.05 ($r_s = -0.812$; $p = 0.0079$) as seen in **Table 5**. However, this association was not statistically significant at the 5% level after Benjamini–Hochberg correction ($q = 0.063$). Distance was measured from a single reference point rather than from specific emis-

sion areas within the landfill, and measurements were conducted at different times. Consequently, these correlations may have been influenced not only by spatial differences but also by sampling time, wind conditions, landfill operations, and local emission sources. The results should therefore be interpreted as exploratory spatial associations rather than as causal distance–concentration relationships or definitive evidence of landfill-source attribution.

In **Figure 5**, the general profile accords with a source–transport–receptor scheme. Formally, concentration at a receptor point can be modeled as a linear combination of source strength, atmospheric transport pathways, and receptor location. Exposure comprises several elements, with distance being one; however, receptor concentration largely depends on plume orientation, wind speed, atmospheric stability, sampling time interval, operational activity in surrounding plants, and local sources.

Table 5. Spearman correlations between distance and pollutant concentration.

Parameter	Spearman's r_s	p -Value	Benjamini–Hochberg q -Value
PM _{1.0}	−0.353	0.351	0.592
PM _{2.5}	−0.293	0.444	0.592
PM ₁₀	−0.293	0.444	0.592
HCHO	−0.426	0.253	0.592
TVOC	−0.812	0.0079	0.063
CO	−0.603	0.085	0.342
CO ₂	0.100	0.798	0.798
LEL	−0.237	0.539	0.616

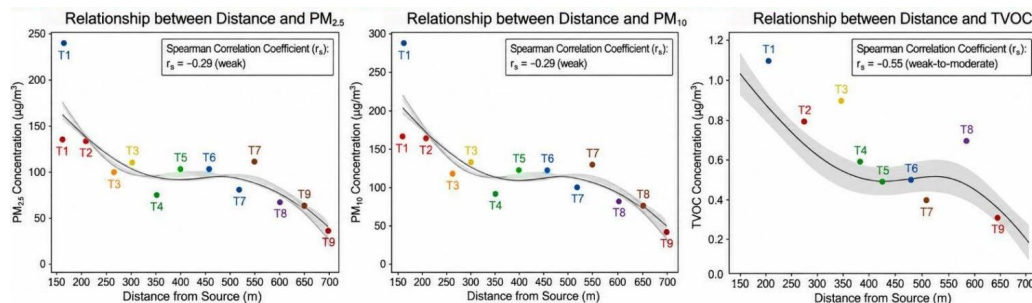


Figure 5. Scatter plots showing relationships between distance from the source-reference point and concentrations of PM_{2.5}, PM₁₀, and TVOC. Labels indicate specific measurement locations.

3.7. Formaldehyde and TVOC

HCHO concentrations across the monitoring locations ranged from 1.00 to 4.00 μg/m³. The highest concentration was recorded at Point 1, located 340 m from Point 0. The lowest reported values occurred at Points 3, 5, and 9. Overall, the measurements did not show a consistent pattern of decreasing HCHO concentration with increasing distance

from Point 0. At Point 8, located 200 m from Point 0, the measured HCHO concentration was 3.00 μg/m³. At Point 9, located 375 m from Point 0, the reported concentration was lower. These observations further illustrate the absence of a simple monotonic distance–concentration relationship. All measured HCHO values were numerically below the WHO 30-min guideline value of 0.1 mg/m³. However, these measurements cannot be used to determine compliance with

the guideline. First, the data in this study were calculated as 60-min averages rather than the 30-min averages specified by the guideline. Second, the detection and analytical performance of the portable sensors used in this study require further validation. Therefore, the measurements alone cannot establish that formaldehyde exposure in the study area is within a safe range.

TVOC concentrations ranged from 0.30 to 1.10 $\mu\text{g}/\text{m}^3$. The highest value was recorded at Point 8 (200 m), followed by 0.9 $\mu\text{g}/\text{m}^3$ at Point 1 and 0.8 $\mu\text{g}/\text{m}^3$ at Point 7. The lowest value was recorded at Point 4 (640 m). This pattern is broadly consistent with the observed negative correlation between TVOC and distance. However, TVOC is an aggregate measurement and cannot confirm the presence of benzene, toluene, ethylbenzene, xylene, or any other specific compound. Landfill studies using compound-specific analytical techniques have shown that VOC composition may differ between operational areas and surrounding environments and may vary with meteorological conditions and landfill-management processes^[21,27]. Accordingly, TVOC should be interpreted as a screening indicator of mixtures of organic emissions rather than as a means of identifying specific sources or estimating compound-specific health risks. VOC speciation using sorbent-based sampling followed by GC-MS analysis would be required to characterize chemical composition and potential sources.

3.8. CO, CO₂, CH₄, H₂S, O₂, and LEL

CO concentrations were highly heterogeneous across the monitoring locations. Point 7 recorded the highest concentration at 43 ppm, followed by Point 2 at 30 ppm and Points 8 and 9 at 12 ppm each. CO was not detected at Points 1, 4, 5, and 6. This pattern suggests that measured CO may have been influenced by transient sources such as incomplete combustion or vehicle emissions. The correlation between CO concentration and wind speed was notable in the observational dataset (Spearman's $r_s = 0.812$; $p \approx 0.008$). However, this association should not be interpreted as evidence that wind generated CO. Point 7 simultaneously recorded the highest CO concentration and the highest wind speed and therefore strongly influenced the observed correlation. Wind may influence CO concentrations through two competing processes: transport of CO-containing air masses toward the detector, which can increase measured concentrations, and at-

mospheric dispersion, which can enhance dilution. Given the limited sample of nine observations, the available statistical analysis cannot distinguish between these processes.

CO₂ concentrations ranged from 380 to 699 ppm, with a mean of 562.78 ppm. Mean CO₂ concentrations differed only slightly between the near and outer zones, and no clear spatial gradient was evident. Point 4 recorded the highest CO₂ concentration, whereas Point 3 recorded the lowest. These observations suggest that ambient CO₂ concentrations may have been influenced by regional background conditions, prevailing winds, anthropogenic activities, and vegetation, rather than by distance from the landfill alone. CH₄ and H₂S were not detected at any sampling location, while O₂ remained stable at 20.9% across all locations. The non-detection of CH₄ and H₂S does not demonstrate that these gases were not produced by the landfill. Emissions may have been intermittent, may have occurred outside the sampling periods, or may have followed transport pathways that did not intersect the monitoring locations. Furthermore, the portable gas detector was primarily designed for occupational-safety applications, and its detection limit may have exceeded ambient concentrations in the field. Therefore, zero readings should be interpreted in relation to the instrument's detection limits and resolution and should not be considered conclusive evidence of the absence of these gases.

LEL readings ranged from 3% to 11% LEL, with the highest value recorded at Point 6. LEL is not a direct measurement of methane concentration; rather, it represents the instrument's response to combustible gases relative to the lower explosive limit of the calibration gas. Thus, the instrument registered combustible-gas responses, but these readings cannot be converted directly into the concentration of a specific gas. The simultaneous occurrence of zero CH₄ readings and LEL responses of 3–11% requires further verification using the official instrument documentation, particularly with respect to channel configuration, calibration gas, response factors, and output units. Unless the calibration and response characteristics are fully documented, field LEL readings should not be interpreted as definitive evidence of atmospheric safety or regulatory compliance.

3.9. Synthesis and Scientific Contributions

The first major finding concerns the spatial variability of airborne particulate matter. Particulate concentrations

differed significantly among the monitoring locations, indicating that pollutant distribution throughout the study area was highly heterogeneous. Points 7 and 9 recorded the highest particulate concentrations among the nine locations.

Second, the mean concentrations of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} in the near zone were approximately 3.6–3.7 times those in the outer zone. Although these differences were substantial in magnitude, they did not reach conventional levels of statistical significance. Consequently, the presence of a true and persistent zonal difference cannot be confirmed from the available dataset.

Third, TVOC showed the strongest negative association with distance among the measured pollutants. Before adjustment for multiple testing, TVOC concentrations decreased with increasing distance from the reference point, with $r_s = -0.812$. However, after multiple-testing correction, the association no longer met the conventional 5% significance threshold. It should therefore be interpreted as an exploratory pattern rather than as a confirmed distance-dependent relationship.

Fourth, the results challenge the assumption that pollutant concentrations necessarily increase consistently with decreasing distance from a landfill. The closest monitoring location did not record the highest concentrations. Instead, measured pollutant concentrations appeared to reflect the combined influence of plume direction, atmospheric dilution, measurement timing, nearby operational activities, local land-use conditions, and other local emission sources. The landfill represents one potential source within a more complex source–transport–receptor system.

The principal contribution of this study is not the establishment of an absolute causal relationship between landfill emissions and pollutant exposure in surrounding communities. Rather, its primary value lies in providing baseline data for multiple pollutants across nine distinct small-scale microenvironments surrounding an open urban municipal-waste landfill in a tropical setting. Such information can help identify areas requiring additional monitoring, guide monitoring priorities, and identify parameters warranting more detailed investigation. The findings also highlight a limitation of purely distance-based assessments of air quality. Without information on plume behavior, background conditions, and nearby emission sources, geographic distance alone may serve as an inadequate proxy for exposure. Because no simul-

taneous measurements were conducted at verified upwind or background locations, the landfill-specific contribution could not be separated from background concentrations and other local sources. The results should therefore be interpreted as short-term pollutant patterns and potential hotspots rather than as confirmed landfill-attributable hotspots. Portable sensors are useful for baseline surveys and initial spatial screening because of their mobility, relatively low cost, and ease of deployment. However, their measurements can be influenced by meteorological conditions, interference from other pollutants, and sensor drift. Wider deployment therefore requires standardized procedures, regular quality-control checks, and periodic comparison with reference-grade instruments. Machine-learning and data-fusion approaches may further improve measurement accuracy, provided that models are trained and validated using appropriate site-specific data.

3.10. Potential Health Implications

Particulate matter is associated with adverse respiratory and cardiovascular effects. PM_{10} can penetrate the respiratory tract, whereas $PM_{2.5}$ can reach deeper regions of the lungs and may enter the bloodstream. Previous studies have associated exposure to particulate matter with respiratory irritation, reduced lung function, exacerbation of asthma, cardiovascular disease, and all-cause mortality. These effects may be of particular concern for children, older adults, and individuals with pre-existing respiratory or cardiovascular conditions^[28]. Similar concerns regarding ambient air quality and respiratory health among communities living near landfill sites have been reported elsewhere^[29]. The Tamangapa Landfill is located close to residential areas. A local household survey reported that approximately 76% of residents had lived near the landfill for more than 10 years^[22]. Long-term residence in the area may increase the potential for repeated exposure to environmental pollutants originating from multiple local sources.

Waste pickers working directly within the landfill may experience particularly frequent contact with landfill-related environmental hazards because of the amount of time they spend within the operational area. In the 2021 census, this group reportedly comprised approximately 150 households; by 2025, 101 individuals remained. A recent health assessment reported respiratory complaints among 76.7% of the

waste pickers, including persistent coughing, chest tightness, and wheezing^[24].

These observations highlight the importance of considering cumulative and combined exposures rather than evaluating pollutants exclusively in isolation. Communities may be exposed to mixtures of particulate matter, HCHO, TVOC, CO, and other pollutants over extended periods. Potential effects of such co-exposures may not be fully captured through single-pollutant assessments alone. In addition to long-term exposure, short-term episodes of elevated pollutant concentrations, such as those observed at Points 7 and 9, may also warrant further investigation. The potential health consequences of repeated background exposure combined with episodic concentration peaks should therefore be evaluated in future epidemiological studies.

However, direct comparisons among studies are limited by differences in landfill characteristics, pollutant sources, monitoring duration, and measurement methods. Furthermore, the measurements in the present study do not represent individual-level exposure, exposure frequency, or duration of residence or activity at each monitoring location. Consequently, they cannot be used to determine long-term personal exposure or directly estimate health effects among nearby residents. The 60-min PM concentrations measured in this study should not be directly compared with WHO guideline values of 15 $\mu\text{g}/\text{m}^3$ for the 24-h mean of PM_{2.5} and 45 $\mu\text{g}/\text{m}^3$ for the 24-h mean of PM₁₀ for the purpose of determining guideline exceedance or health risk. The averaging periods are not equivalent. Accordingly, WHO guideline values are presented only to contextualize the observed concentrations and not as short-term compliance limits. Future studies should consider repeated or continuous 24-h monitoring to support cumulative exposure assessment. Epidemiological surveys, personal-exposure monitoring, and formal health-impact assessments would also be required to investigate potential effects among surrounding communities.

4. Management Implications

The findings indicate a need for a more comprehensive monitoring system capable of capturing spatial, temporal, and meteorological variability across the study area. Reliable interpretation of air-quality patterns requires data collected across multiple locations, time periods, and environmental

conditions. Future air-quality monitoring should therefore include simultaneous observations at four key types of locations: a verified upwind background site, an active landfill operational area, the landfill boundary, and surrounding residential areas. A confirmed upwind site can serve as a background reference when it is demonstrably outside the influence of the landfill plume during the monitoring period. All monitoring activities should comply with applicable national environmental regulations^[30].

This study proposes a three-stage management approach. The first stage comprises low-cost actions that can be implemented immediately. These include prohibiting open waste burning, strengthening road-dust control, imposing vehicle-speed limits within the landfill, requiring freight vehicles to cover their loads, periodically applying water to internal roads during dry conditions to suppress dust, and improving the stabilization or covering of exposed waste surfaces. These measures are intended to reduce uncontrolled emissions of particulate matter and other pollutants. The second stage involves medium-term improvements to the monitoring program. Monitoring at Points 7 and 9 should prioritize particulate matter because these locations recorded the highest particulate concentrations during the present survey. Point 8 should receive particular attention for analysis of TVOC-related spatial patterns because it recorded the highest TVOC concentration despite relatively low particulate concentrations. Fixed monitoring stations should also be considered at verified upwind, landfill-boundary, and downwind locations. Under the proposed monitoring scheme, key locations could be sampled weekly, while background-reference monitoring could be conducted monthly. Additional seasonal campaigns during both wet and dry seasons would provide a more complete understanding of temporal variations in air quality. The third stage involves longer-term infrastructure improvements, including paving currently unpaved internal roads, constructing more enclosed waste-unloading areas, establishing a permanent long-term air-quality monitoring network, and improving landfill-gas collection infrastructure. Such measures should be implemented progressively, based on monitoring evidence, operational feasibility, and available funding.

If monitoring infrastructure is upgraded, Points 7 and 9 should be considered priority locations for enhanced particulate monitoring because they exhibited the highest short-term

particulate concentrations in the present study. Point 8 also warrants additional investigation because it is the closest monitoring point to Point 0 and exhibited an unusual combination of very low particulate concentrations and the highest observed TVOC concentration. Continued monitoring at fixed locations could help distinguish the relative influences of distance, geographic orientation, prevailing wind direction, and other local factors. However, this would require sufficient repeated observations under a range of meteorological and operational conditions.

Portable air-quality sensors are well suited to preliminary field surveys and rapid identification of potential pollution hotspots. They are lightweight, mobile, and capable of producing measurements without extensive installation. However, portable sensors alone cannot provide definitive validation-grade data. Collocation with reference-grade instruments is necessary to assess their field accuracy and long-term performance. PM measurements should be compared with gravimetric reference methods, VOC measurements with sorbent-tube sampling followed by GC-MS, and formaldehyde measurements with standardized active or passive sampling methods. Calibration and analytical procedures should follow established standards and be documented thoroughly to ensure traceability.

Future monitoring should extend over longer periods and include simultaneous measurements at verified background or upwind locations, landfill boundaries, and downwind residential areas under a range of meteorological and operational conditions. Detailed chemical characterization and formal source-apportionment analyses would further help distinguish landfill emissions from other local sources. Community-based reporting and sensor monitoring may complement professional monitoring by identifying smoke, odors, dust events, or suspected open-burning episodes. However, community-generated data require appropriate training, standardized procedures, and independent quality-control checks and should not replace reference-grade environmental monitoring.

5. Limitations

Several important limitations must be considered when interpreting the findings of this study. First, monitoring

was conducted at only nine locations, with a single 60-min measurement at each site. The resulting sample size was therefore too small to support strong inferential conclusions. Statistical results, including *p*-values, adjusted *q*-values, correlation coefficients, and effect sizes, should be regarded as exploratory indicators rather than definitive evidence. Furthermore, measurements were not conducted simultaneously across all locations but sequentially at different times of day. Consequently, factors other than spatial location could not be held constant throughout the monitoring period. Differences among sites therefore reflect an inseparable combination of spatial location, temporal variability, meteorological conditions, landfill operational status, traffic, and other local activities. The contribution of each individual factor cannot be reliably disentangled from the present dataset.

Second, the study did not include simultaneous measurements at verified upwind or background-reference locations. Therefore, the landfill-specific contribution to the observed pollutant concentrations could not be quantified. If background and landfill-area measurements had been collected concurrently, background-adjusted concentration differences could have been estimated. Without such control measurements, the independent contribution of landfill emissions to local air quality remains uncertain. Third, the spatial distribution of monitoring points was uneven, and all distances were calculated from a single reference point rather than from individual pollutant-emission areas or the landfill boundary. Consequently, the measurements may not represent the spatial influence of specific emission zones within the landfill. Fourth, several analytical components that would be required for detailed source characterization were not included. These include VOC-speciation analysis, chemical characterization of particulate matter, particle-number distribution measurements, and formal source-apportionment analysis. Therefore, the measured TVOC concentrations and particulate-fraction ratios cannot identify specific chemical compounds, characterize the toxicity of complex pollutant mixtures, or determine the precise source of measured pollution. Overall, the results should be interpreted as preliminary, screening-level observations describing short-term pollutant variability rather than as definitive evidence of long-term pollutant distributions, source contributions, or population exposure.

6. Conclusion

Short-term air-quality measurements conducted at nine locations around the Tamangapa Landfill demonstrated substantial variability in atmospheric pollutant concentrations among sites. Among the measured parameters, $PM_{1.0}$, $PM_{2.5}$, PM_{10} , and CO showed the greatest spatial variability. The highest particulate concentrations were recorded at Point 9, located 375 m from the reference point. In contrast, Point 8, the closest monitoring point to Point 0 at a distance of 200 m, recorded unexpectedly low particulate concentrations. These observations indicate that short-term pollutant concentrations were not determined solely by distance from the reference point. When the monitoring locations were classified into near and outer zones, mean $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations in the near zone were approximately 3.6–3.7 times higher than those in the outer zone. Mean HCHO, TVOC, and CO concentrations were also higher in the near zone. However, none of the zonal differences reached conventional statistical significance. Effect-size analysis indicated moderate differences for several parameters, whereas TVOC exhibited the largest effect size. TVOC showed a strong negative correlation with distance from the reference point ($r_s = -0.812$). However, after correction for multiple testing, the association did not remain statistically significant at the 5% level. This relationship should therefore be considered exploratory rather than conclusive. The spatial distribution of pollutants is better interpreted within a source–transport–receptor framework than through distance alone. Plume direction, wind speed, measurement time, landfill operational activities, and other local emission sources should be considered when interpreting pollutant concentrations and transport patterns. The findings of this study represent preliminary screening-level observations obtained using portable sensors and are subject to important limitations. They should not be interpreted as regulatory-grade evidence, as estimates of long-term population exposure, or as definitive source-apportionment results. Future studies should conduct simultaneous and repeated sampling at verified upwind background locations, landfill boundaries, and downwind receptor locations; collect measurements across different times of day and seasons; characterize direct emissions from the landfill and nearby sources; and collocate portable sensors with calibrated reference instruments to

evaluate sensor performance. More detailed characterization of TVOC constituents and the chemical composition of particulate matter will also be necessary to improve source identification and support health-risk assessment. Continuous multi-location monitoring under a variety of meteorological conditions, along with repeated sampling at individual sites, would help separate spatial and temporal effects, generate more representative time-weighted concentrations, and provide a more reliable characterization of ambient air-quality conditions.

Author Contributions

Conceptualization, data curation, investigation, S.Y.; visualization, supervision, I.M.; methodology, M.H.; formal analysis, S.Y., M.H., and M.R.A.F.; validation, I.M. and M.H.; writing—review & editing, M.R.A.F. and A.S.P.; conceptual discussion, A.S.P. All authors have read and agreed to the published version of the manuscript.

Funding

This study was supported by research funding for higher education awarded by the Directorate of Research and Community Service (DRPM), Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, and administered through the Institute for Research and Community Service (LP2M), Universitas Muslim Indonesia. Regular Fundamental Research Program, under Contract No. 1403-25/B.07/UMI/V/2026. The authors express their sincere appreciation and gratitude for this valuable support.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable. This study does not involve human subjects.

Data Availability Statement

The manuscript included all required data and the implementation of information.

Conflicts of Interest

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

AI Use Statement

During the preparation of this work, the authors used Chat GPT-3.0 to improve readability and language understanding. After utilizing this AI technology, the authors meticulously reviewed and amended the content as required, ensuring its accuracy and completeness. The authors assume complete accountability for the content of the publication.

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