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ORIGINAL RESEARCH ARTICLE

Spatial and temporal variation of $PM_{2.5}$, TVOC, formaldehyde and combustion gases around a tile manufacturing facility in Kachi Town, Dutse, Jigawa State, Nigeria

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ABSTRACT

Industrial facilities that process minerals can raise ambient concentrations of particles and gases in nearby communities, but local evidence on how far the effect extends and when it peaks is scarce in northern Nigeria. Fine particulate matter ($PM_{2.5}$), formaldehyde (HCHO), total volatile organic compounds (TVOC), carbon monoxide (CO), carbon dioxide (CO_2), temperature and relative humidity were measured with one portable multi-parameter monitor at five locations (the fenceline, receptors at 100 m, 500 m and 1 km, and a comparison location at 2 km) in the morning, afternoon and evening of three consecutive days (45 readings). Because the same nine sessions were sampled at every location, spatial differences were assessed with the blocked Friedman test and Wilcoxon signed-rank comparisons with the 2 km location (Holm-adjusted), and temporal differences with the Friedman test. The results revealed a consistent decline in concentrations with increasing distance from the facility. Mean $PM_{2.5}$ decreased from 106.11 µg/m^3 at the fenceline to 34.67 µg/m^3 at 2 km; HCHO from 0.063 to 0.033 mg/m^3; TVOC from 0.182 to 0.061 mg/m^3; CO from 3.11 to 1.00 ppm; and CO_2 from 529 to 435 ppm. This indicates a clear spatial attenuation of the measured concentrations with increasing distance from the facility. All five parameters differed among locations (Friedman $p < 0.001$; $W = 0.87–1.00$). In Holm-adjusted pairwise comparisons with the 2 km location, all five were higher at the fenceline (0 m) and 100 m (adjusted $p = 0.016$), all except CO at 500 m, and at 1 km $PM_{2.5}$ and TVOC ($p = 0.016$) and, marginally, HCHO ($p = 0.039$) remained higher; CO and CO_2 did not differ from the comparison location ($p = 0.50$ and 0.19). Temperature and humidity did not differ among locations. All parameters varied with time of day (Friedman $p \leq 0.007$) and were highest in the afternoon (mean $PM_{2.5}$ 53.5, 77.9 and 61.8 µg/m^3 in the morning, afternoon and evening), and the afternoon increase in $PM_{2.5}$ was four times larger at the fenceline than at 2 km. Day-to-day differences were smaller. The gradient and the afternoon peak are consistent with a local source at the facility, but wind direction, production activity, traffic and other sources were not recorded, so the facility's contribution cannot be established. Wind-resolved, seasonal monitoring with calibrated instruments is needed to confirm attribution.

Keywords: ambient air quality; $PM_{2.5}$; tile manufacturing; spatial and temporal variation; Jigawa State

Introduction

Ambient air quality describes outdoor air in terms of the substances it contains and the concentrations to which people are exposed. Air pollution is a major and growing health burden in Africa: Fisher et al. (2021) estimated that it caused 1.1 million deaths across the continent in 2019, of which 394,000 were attributed to ambient pollution, and that ambient

pollution is increasing. Industrial development can bring employment and construction materials, but its benefits depend partly on how emissions are managed. Communities near mineral-processing facilities may be exposed to dust, including fine particulate matter with a diameter of 2.5 µm or less ($PM_{2.5}$), from production, storage and transport, along with combustion emissions from vehicles and power generation. Measuring these pollutants is necessary to separate visible nuisance from air-quality concerns.

Tile manufacture covers different technologies with different emission profiles. Ceramic tiles are formed from prepared mineral materials and fired, whereas natural stone tiles are produced by cutting and finishing stone. Mechanical handling of mineral materials can release dust, while fuel-burning equipment and vehicles add combustion products such as carbon monoxide (CO) and carbon dioxide (CO_2). In ceramic production, thermal breakdown of organic additives and decoration materials can also release volatile organic compounds (VOCs) and aldehydes such as formaldehyde (HCHO), which are commonly measured together as total volatile organic compounds (TVOC) (Ferrari & Zannini, 2017). Around ceramic plants in Spain, anthropogenic activity was found to determine particulate levels in an industrial–urban area (Vicente et al., 2011), and ceramic-industry emissions were linked to metals in ambient PM_{10} (Minguillón et al., 2009). In a Brazilian ceramic district, mean PM_{10} was 77.75 µg/m^3 in Santa Gertrudes and 42.59 µg/m^3 in Rio Claro, compared with 29.52 µg/m^3 in a control town, and the particles were mostly silica; higher silica-rich PM_{10} was associated with poorer lung function in adolescents (Mizutani et al., 2023). Near a tile and ceramic factory in Iran, the highest mean $PM_{2.5}$ was about 0.013 mg/m^3 (Taghizadeh et al., 2023).

In Nigeria, receptor monitoring around industrial plants has concentrated on cement works and urban industrial estates. At a cement complex in Ogun State, SO_2 and NO_2 exceeded limits at several fenceline locations, while 24-hour CO and volatile organic compound concentrations stayed within limits (Adeniran et al., 2019). At a cement plant in Cross River State, gases and particles at quarrying, milling and loading sites showed significant month-to-month differences and an air quality index in the Very Unhealthy to Hazardous range (Nwogu et al., 2025). In the Sharada industrial area of Kano, mean PM_{10} was 422.44 µg/m^3 at industrial sites and 187 µg/m^3 at residential sites (Tafida & Gana, 2025). Health evidence near mineral-processing plants comes, for example, from Zambia, where residents within 1 km of a cement factory reported more respiratory symptoms than those of a control community 18 km away (Nkhama et al., 2017).

Background levels across northern Nigeria are high and variable. Ground-based $PM_{2.5}$ in Kano reached 90–270 µg/m^3 in the Harmattan and 6.59–15.42 µg/m^3 in the rainy season (Idris et al., 2025), and a network of 15 sites in eight sub-Saharan countries recorded annual mean $PM_{2.5}$ between 10 and 116 µg/m^3, with seven Nigerian sites higher in the dry season (Awokola et al., 2022). That network also showed daily cycles, with $PM_{2.5}$ commonly peaking at about 06:00 and 18:00, a pattern attributed to traffic. Because the background is high and variable, an assessment of a single facility needs a comparison location, repeated measurements during the day, and a clear statement of the measurement conditions. Temperature and humidity follow a strong daily cycle and are associated with $PM_{2.5}$, but much of that association arises from covariation with the weather systems that transport air, not from

direct dependence (Tai et al., 2010, 2012), so correlations with weather must be read as descriptive.

Two features of the existing evidence base therefore limit what is known about tile plants in Nigeria. First, published ambient studies of tile and ceramic plants come mainly from Europe, Brazil and Iran and concern ceramic production; they therefore provide technological comparisons rather than direct evidence for a facility in Jigawa State. Second, little is known about how far the effects of such a facility extend beyond its boundary and when concentrations are highest, although both matter for the siting of homes and schools and for the design of monitoring. Kachi Town in Dutse Local Government Area hosts a tile manufacturing facility that is reported locally to produce granite tiles, and no measured air-quality data have been published for its surroundings. This study aimed to determine the spatial variation (with distance from the facility) and temporal variation (between morning, afternoon and evening, and between days) of ambient $PM_{2.5}$, HCHO, TVOC, CO and CO_2 around the tile manufacturing facility in Kachi Town, Dutse Local Government Area, Jigawa State, Nigeria.

Materials and methods

Study area

The study was carried out in Kachi Town, Dutse Local Government Area, Jigawa State, north-western Nigeria. The Kachi locality is at approximately 11.71623° N, 9.35045° E (GeoNames, n.d.); this gazetteer point identifies the locality and is not a measured coordinate of the facility or of any sampling station. The climate is tropical, with a rainy season generally running from about May to September or October and a dry season that includes the Harmattan period. Measurements were made on 4, 5 and 6 October 2026, late in the rainy season. The facility is reported locally to be a granite-tile factory, but information on its production route, fuels, production schedule, dust-control arrangements and site inventory was not available, so it is described throughout only as a tile manufacturing facility.

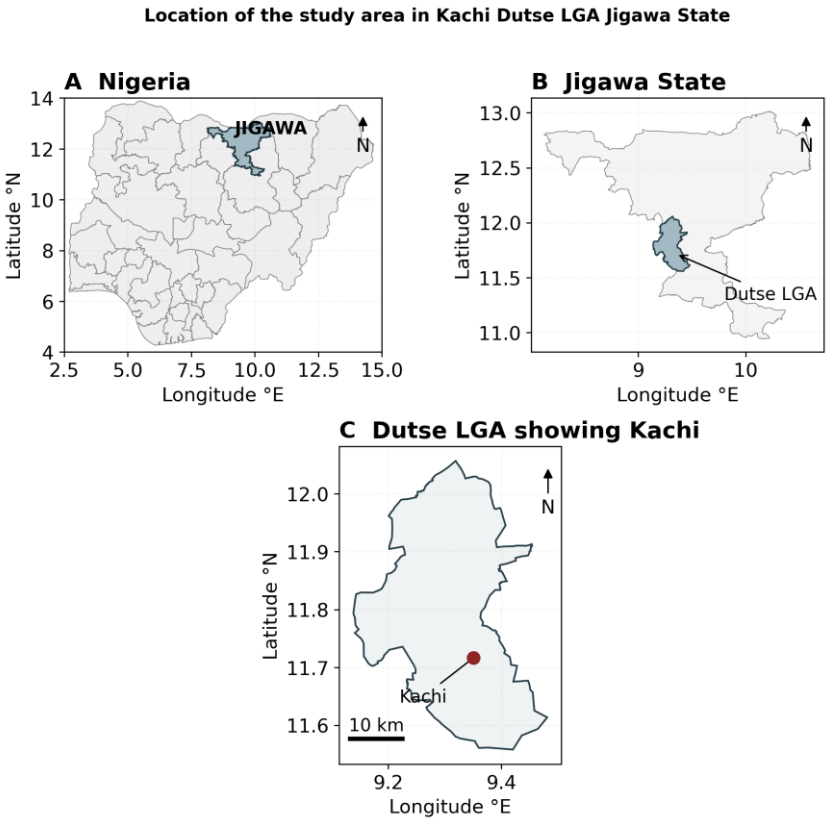


Figure 1: Location of the study area in Kachi Dutse LGA Jigawa State

Sources: geoBoundaries gbOpen Nigeria ADM1 and ADM2 based on GRID3 data under CC BY 4.0, and GeoNames ID 9410381, accessed 2 October 2026. The Kachi point is a locality reference; sampling coordinates were not recorded.

Study design and sampling locations

The study was a field-based observational study with repeated measurements. Five sampling locations were purposively selected, partly on the basis of accessibility, along a transect extending from the fenceline of the facility to a comparison location approximately 2 km away (Table 1; Figure 2). Wind direction was not recorded, so the locations cannot be described as downwind of the facility. Because locations were chosen partly for accessibility and not at random, the distances between them are uneven and the sites may not represent the whole surroundings of the facility. At each location, readings were recorded in the morning, afternoon and evening over three consecutive days, giving nine readings per location and 45 readings in total. Sessions started at 09:00 (morning), 13:00 (afternoon) and 17:00 (evening) on each day. The design supports comparison between locations (spatial variation), between times of day and days (temporal variation), and with concurrent temperature and relative humidity. The study did not manipulate the facility's operations and did not include a period when the plant was not operating. The design therefore cannot separate the facility's contribution from that of other local sources, and differences between locations are described as spatial patterns that are consistent with, but do not prove, a contribution from the facility.

Table 1: Description of the sampling locations around the tile manufacturing facility

Code	Role	Approximate distance from the facility
A	Fenceline	0 m
B	Receptor	100 m
C	Receptor	500 m
D	Receptor	1 km
E	Comparison location	2 km

Note: GPS coordinates of the sampling locations were not recorded; distances are approximate

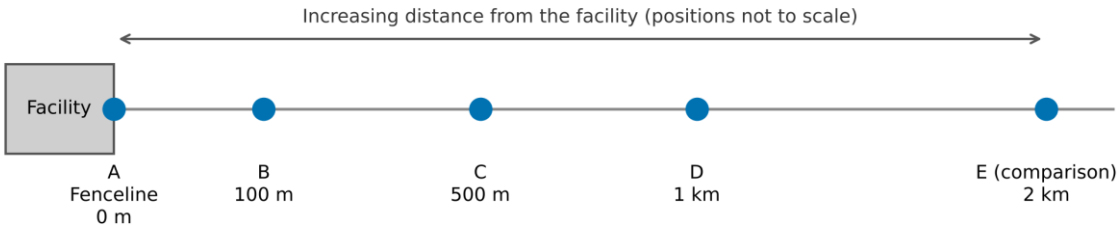


Figure 2: Schematic of the sampling design. Locations are shown in order of distance from the facility; the figure is not a map and positions are not to scale.

Instrument and measurement protocol

Air-quality measurements were obtained using a portable multi-parameter air-quality monitor (Henan Bosean Electronic Co., Ltd. (BOSEAN)), which simultaneously measured fine particulate matter ($PM_{2.5}$, μg/m^3), formaldehyde (HCHO, mg/m^3), total volatile organic compounds (TVOC, mg/m^3), carbon dioxide (CO_2, ppm), carbon monoxide (CO, ppm), air temperature (°C) and relative humidity (%). The same instrument was used across all sampling locations and measurement sessions to ensure procedural uniformity. At each location, the monitor was positioned 1.5 m above ground level and allowed to stabilise for 10 minutes before measurements were recorded. The CO and CO_2 values are indirect estimates from the instrument and not outputs of dedicated analysers, and CO is reported in whole ppm. HCHO and TVOC sensors respond to groups of compounds and not to individual ones, so their values are screening indicators. Wind speed and direction, production activity and traffic were not recorded. All nine readings were successfully obtained for each parameter at every sampling location, with no missing values requiring estimation, substitution or replacement.

Data analysis and hypotheses

Two null hypotheses were tested at a significance level of 0.05. $H0_1$: there is no difference in the concentrations of $PM_{2.5}$, HCHO, TVOC, CO and CO_2 among the five locations. $H0_{2a}$: there is no difference among the morning, afternoon and evening sessions. $H0_{2\beta}$: there is no difference among the three days.

For each parameter and location, the mean, standard deviation, minimum and maximum of the nine readings were calculated, and means by time of day and by day were calculated across locations. With nine readings at each location and no assumption of normality, non-parametric procedures were used. Differences among the five locations ($H0_1$) were tested for each parameter with the Friedman test (Friedman, 1937), treating the nine day-and-period

sessions as blocks, so that all locations are compared within the same session and the shared effects of day and time of day are removed; Kendall's W was the effect size (Kendall & Babington Smith, 1939). Each location was then compared with the comparison location E using Wilcoxon signed-rank tests on the paired session readings (Wilcoxon, 1945). The Holm method (Holm, 1979) was applied within each parameter, as a family of four comparisons with location E; no adjustment was made across parameters. With nine pairs the smallest attainable two-sided exact p-value is 0.0039, which becomes 0.016 after Holm adjustment, so the adjusted values cannot go lower. For comparison with the unpaired approach, the Kruskal–Wallis test (Kruskal & Wallis, 1952; effect size $\varepsilon^2 = H / (N - 1)$, with values of 0.14 or more commonly regarded as large; Tomczak & Tomczak, 2014) and Mann–Whitney U tests (Mann & Whitney, 1947) were also computed. The monotonic association between distance and concentration was assessed with Spearman's rank correlation coefficient (Spearman, 1904). Statistical analyses were run with the assistance of Claude (Anthropic; claude.ai), which executed the tests in Python 3.13 with SciPy 1.18, pandas 3.0 and NumPy 2.5. The authors checked the outputs and take responsibility for the analysis.

Differences among times of day ($H0_{2a}$) and among days ($H0_{2\beta}$) were tested with the Friedman test (Friedman, 1937). The 15 combinations of location and day served as blocks for time of day, and the 15 combinations of location and period served as blocks for day, with Kendall's coefficient of concordance W as the effect size (Kendall & Babington Smith, 1939). Pairwise differences between periods or days were examined with Wilcoxon signed-rank tests (Wilcoxon, 1945) with Holm adjustment. The contrast between the fenceline and the comparison location was expressed as the difference between the means at A and E, and as a percentage of the mean at A; this assumes that location E represents background conditions, which was not verified. For context, CO in ppm was converted to mg/m^3 using 1 ppm ≈ 1.15 mg/m^3 (25 °C, 1 atmosphere).

The readings at one location are repeated measurements at a single site, not independent replicates, and the same days and periods were sampled at every location. The blocked Friedman and Wilcoxon tests account for this structure, and are the primary tests. The Kruskal–Wallis and Mann–Whitney tests assume independent groups and treat the day and period of each reading as an uncontrolled source of variation, so they, and the Spearman coefficients, are reported as descriptive. Because the nine sessions are three days at one site, the tests describe these days and do not support generalisation to other plants or seasons. The statistical tests were limited to assessing differences and associations among the measured variables. Wind direction, production records and traffic data were not available, so source attribution could not be established statistically.

Results

Concentrations at the five locations

The data set was complete, with nine readings at each of the five locations for every parameter. All five measured parameters were highest at the fenceline (A) and lowest at the comparison location (E), and concentrations fell progressively at the intermediate locations

(Table 2; Figure 2). Temperature and relative humidity were practically the same at all five locations.

Table 2: Mean ± standard deviation of air-quality parameters across the five sampling locations (n = 9 readings per location)

Parameter	A (0 m)	B (100 m)	C (500 m)	D (1 km)	E (2 km)
$PM_{2.5}$ (µg/m^3)	106.11 ± 26.45	84.44 ± 14.96	53.44 ± 7.75	43.33 ± 9.71	34.67 ± 6.98
HCHO (mg/m^3)	0.063 ± 0.0097	0.050 ± 0.0074	0.042 ± 0.0064	0.037 ± 0.0051	0.033 ± 0.0046
TVOC (mg/m^3)	0.182 ± 0.0280	0.144 ± 0.0329	0.109 ± 0.0136	0.077 ± 0.0075	0.061 ± 0.0112
CO (ppm)	3.11 ± 0.60	2.56 ± 0.73	1.56 ± 0.53	1.22 ± 0.44	1.00 ± 0.00
CO_2 (ppm)	529.33 ± 22.51	504.00 ± 25.68	471.33 ± 17.39	448.56 ± 11.61	434.67 ± 26.11
Temperature (°C)	32.44 ± 4.28	31.44 ± 4.90	30.89 ± 5.40	31.33 ± 4.82	31.44 ± 4.75
Relative humidity (%)	40.89 ± 8.98	39.78 ± 10.49	40.78 ± 10.02	40.56 ± 9.70	40.67 ± 10.14

Note. Minimum–maximum at A, B, C, D and E: $PM_{2.5}$ 69–144, 63–107, 44–65, 30–61, 26–48; HCHO 0.050–0.079, 0.041–0.060, 0.035–0.050, 0.032–0.048, 0.028–0.042; TVOC 0.148–0.234, 0.106–0.197, 0.090–0.137, 0.067–0.090, 0.048–0.079; CO 2–4, 2–4, 1–2, 1–2, 1–1; CO_2 496–563, 468–543, 445–503, 430–465, 385–460; temperature 27–38, 25–37, 24–38, 26–38, 24–37; relative humidity 28–53, 25–55, 29–55, 26–54, 28–55.

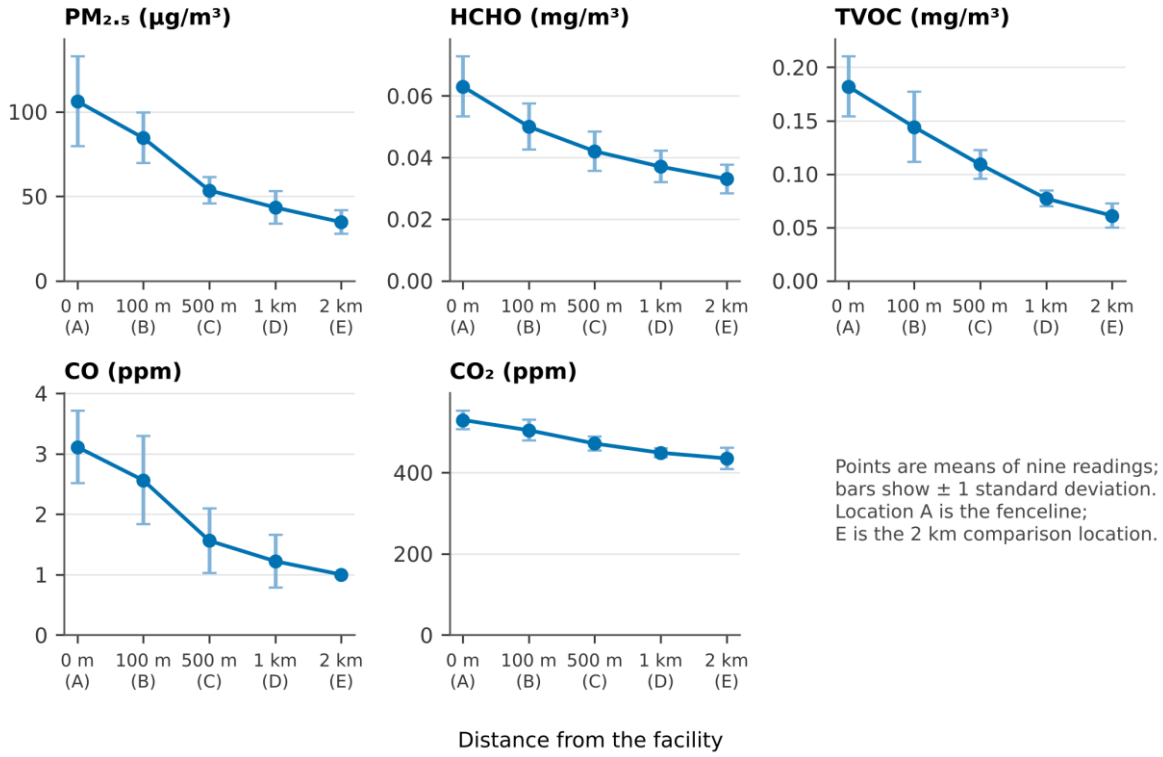


Figure 3: Distance-decay of the five measured parameters. Points are means of nine readings per location; error bars are ± 1 standard deviation (values in Table 2).

Spatial variation

The blocked Friedman tests showed that $PM_{2.5}$, HCHO, TVOC, CO and CO_2 all differed among the five locations (χ^2 = 31.14–35.82, df = 4, $p < 0.001$), with W = 0.87–1.00, meaning that the locations were ranked almost identically in all nine sessions. The unpaired Kruskal–Wallis tests agreed (H = 32.44–38.65, $p < 0.001$, ε^2 = 0.74–0.88), whereas temperature ($p = 0.924$) and relative humidity ($p > 0.99$) did not differ (Table 3). $H0_1$ was therefore rejected for the five parameters. Because temperature and relative humidity showed no differences among sampling locations, the spatial variation in concentrations is unlikely to be driven by microclimatic differences among the locations.

Table 3: Friedman (blocked) and Kruskal–Wallis (unpaired) test results for differences in air-quality parameters across the five sampling locations (df = 4)

Parameter	Friedman χ^2	P	W	Kruskal–Wallis H	p	ε^2
$PM_{2.5}$	35.29	< 0.001	0.98	36.85	< 0.001	0.84
HCHO	33.50	< 0.001	0.93	32.44	< 0.001	0.74
TVOC	35.82	< 0.001	1.00	38.65	< 0.001	0.88
CO	31.14	< 0.001	0.87	33.49	< 0.001	0.76
CO_2	32.27	< 0.001	0.90	35.05	< 0.001	0.80
Temperature	–	–	–	0.90	0.924	0.02
Relative humidity	–	–	–	0.06	> 0.99	0.00

Note. Friedman: 9 blocks (day × period), W = Kendall's coefficient of concordance. Kruskal–Wallis: N = 45, ε^2 = H / (N − 1); it treats the readings as independent and is descriptive (Section 2.4). Temperature and relative humidity were tested with Kruskal–Wallis only.

$PM_{2.5}$ separated the facility from the comparison location more clearly than any other parameter. Mean $PM_{2.5}$ was 106.11 ± 26.45 µg/m^3 at the fenceline and fell to 84.44 µg/m^3 at 100 m, 53.44 µg/m^3 at 500 m, 43.33 µg/m^3 at 1 km and 34.67 µg/m^3 at the 2 km comparison location. The fenceline mean was about three times (3.1) that at E, and nearly three-quarters of the total decline between A and E (52.7 of 71.4 µg/m^3) had occurred by 500 m. Individual readings ranged from 69 to 144 µg/m^3 at the fenceline and from 26 to 48 µg/m^3 at E, so the two locations barely overlapped. TVOC fell about three-fold (0.182 to 0.061 mg/m^3), HCHO about 1.9-fold (0.063 to 0.033 mg/m^3) and CO about three-fold (3.11 to 1.00 ppm), whereas CO_2 at the fenceline was about 95 ppm (22%) higher than at E. Relative to the fenceline, mean concentrations at 500 m were lower by 49.6% for $PM_{2.5}$, 33.0% for HCHO, 40.2% for TVOC, 50.0% for CO and 11.0% for CO_2, and at 2 km by 67.3%, 47.3%, 66.7%, 67.9% and 17.9%, respectively. Concentration was negatively and monotonically related to distance for every parameter (Spearman ρ = −0.91 for $PM_{2.5}$, −0.85 for HCHO, −0.93 for TVOC, −0.85 for CO and −0.88 for CO_2; each $p < 0.001$), although these coefficients treat the 45 readings as independent and are descriptive.

Two features of the gas data need to be noted. At E, all nine CO readings were 1 ppm (standard deviation zero), indicating that E sits at the lowest value the monitor reports and that the true background cannot be resolved. The lowest CO_2 reading at E (385 ppm) was below the outdoor background of about 420 ppm, which indicates sensor uncertainty of at least a few tens of ppm.

Pairwise comparisons with the comparison location show how far the difference extended (Table 4). All five parameters were significantly higher at the fenceline and at 100 m than at E (Holm-adjusted p = 0.016, the smallest value attainable with nine pairs). At 500 m, $PM_{2.5}$, HCHO, TVOC and CO_2 were significantly higher (p = 0.016, 0.016, 0.016 and 0.023), but CO was not (p = 0.125). At 1 km, $PM_{2.5}$ and TVOC (both p = 0.016) and HCHO (p = 0.039) remained significantly higher than at location E, while CO (p = 0.50) and CO_2 (p = 0.19) did not. The HCHO result at 1 km is marginal. The unpaired Mann–Whitney tests gave the same conclusions except for HCHO at 1 km (p = 0.144) and CO at 500 m (p = 0.025), the two comparisons on the margin of significance.

Table 4: Holm-adjusted p-values for pairwise comparisons between each sampling location and reference location E (Wilcoxon signed-rank test on nine paired sessions; family of four comparisons per parameter)

Parameter	A vs E (0 m)	B vs E (100 m)	C vs E (500 m)	D vs E (1 km)
$PM_{2·5}$	0.016 ↑	0.016 ↑	0.016 ↑	0.016 ↑
HCHO	0.016 ↑	0.016 ↑	0.016 ↑	0.039 ↑
TVOC	0.016 ↑	0.016 ↑	0.016 ↑	0.016 ↑
CO	0.016 ↑	0.016 ↑	0.125	0.500
CO_2	0.016 ↑	0.016 ↑	0.023 ↑	0.191

Note. ↑ = significantly higher than at E ($p < 0.05$). 0.016 is the smallest adjusted p attainable with nine pairs. Temperature and relative humidity are omitted because the Kruskal–Wallis test was not significant.

Variation with time of day ($H0_{2a}$)

All parameters differed among morning, afternoon and evening, and the afternoon was highest for all of them (Table 5; Figure 3). Mean $PM_{2·5}$ across all locations was 53.5 µg/m^3 in the morning, 77.9 µg/m^3 in the afternoon and 61.8 µg/m^3 in the evening ($\chi^2 = 25.55$, $p < 0.001$, $W = 0.85$), and all three pairs differed. HCHO was higher in the afternoon than in the morning and the evening, and TVOC and CO_2 differed between all three periods. For CO the effect was smaller ($W = 0.33$) and was confined to morning versus afternoon, probably because whole ppm cannot resolve small changes. Temperature and relative humidity showed the expected daily cycle, with temperature rising from a mean of 25.9 °C to 36.8 °C in the afternoon and relative humidity falling from 51.9% to 30.1%.

Table 5: Variation in air-quality parameters across sampling periods (morning, afternoon and evening), based on mean values across all locations (Friedman test, df = 2, 15 blocks)

Parameter	Morning	Afternoon	Evening	χ^2	p	W	Pairs that differ (Holm)
$PM_{2·5}$ (µg/m^3)	53.5	77.9	61.8	25.55	< 0.001	0.85	All three
HCHO (mg/m^3)	0.041	0.052	0.042	19.40	< 0.001	0.65	Morning–afternoon, afternoon–evening
TVOC (mg/m^3)	0.099	0.132	0.112	20.93	< 0.001	0.70	All three
CO (ppm)	1.6	2.2	1.9	9.94	0.007	0.33	Morning–afternoon
CO_2 (ppm)	461.7	495.1	475.9	18.95	< 0.001	0.63	All three
Temperature (°C)	25.9	36.8	31.9	30.00	< 0.001	1.00	All three
Relative humidity (%)	51.9	30.1	39.5	30.00	< 0.001	1.00	All three

Note. W = Kendall's coefficient of concordance.

The diurnal pattern was present at every location but was strongest at the fenceline (Table 6). At A, mean $PM_{2·5}$ rose from 85.3 µg/m^3 in the morning to 133.7 µg/m^3 in the afternoon, an increase of 48.4 µg/m^3 (57%), before falling to 99.3 µg/m^3 in the evening. The morning-to-afternoon increase was 27.4 µg/m^3 at 100 m, 14.7 µg/m^3 at 500 m, 20.0 µg/m^3 at 1 km and 11.4 µg/m^3 at E, so the absolute increase at the fenceline was about four times that at the comparison location. At every location the evening mean exceeded the morning mean. TVOC showed the same pattern; at the fenceline it rose from 0.157 mg/m^3 in the morning to 0.206 mg/m^3 in the afternoon.

Table 6: Mean $PM_{2.5}$ concentrations (µg/m^3) across the five sampling locations by time of day (n = 3 sampling days per location–time combination)

Location	Morning	Afternoon	Evening
A (0 m)	85.3	133.7	99.3
B (100 m)	70.3	97.7	85.3
C (500 m)	47.0	61.7	51.7
D (1 km)	34.7	54.7	40.7
E (2 km)	30.3	41.7	32.0

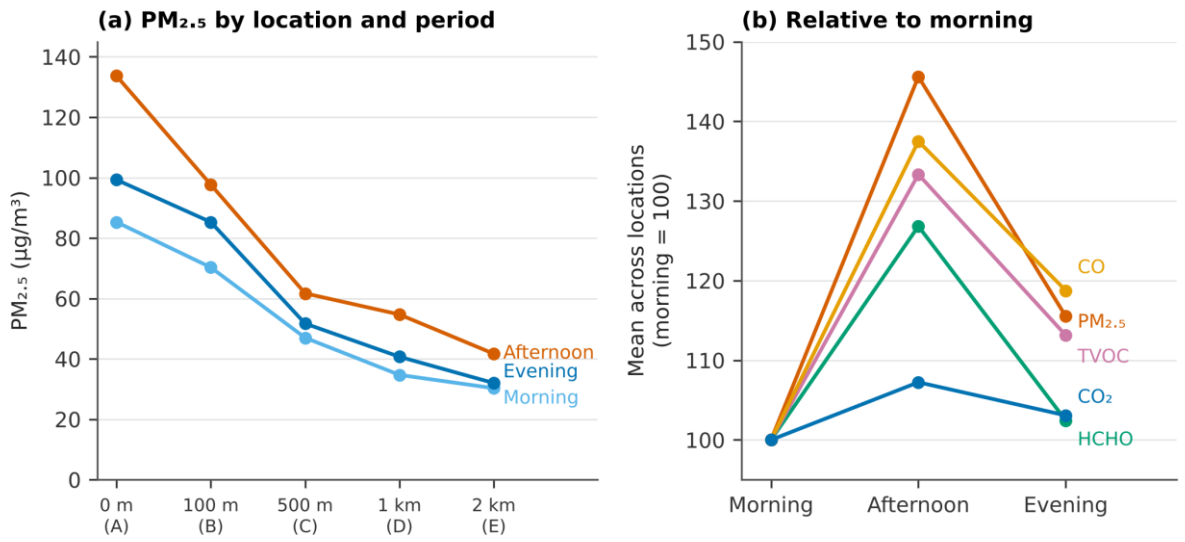


Figure 4: Variation with time of day. (a) Mean $PM_{2.5}$ by location and period (Table 6). (b) Mean of each parameter across locations, expressed relative to the morning mean (= 100), calculated from the rounded means in Table 5.

Day-to-day variation ($H0_{2\beta}$)

$PM_{2.5}$ differed among the three days (63.3, 71.4 and 58.5 µg/m^3; $\chi^2 = 14.52$, $p < 0.001$, $W = 0.48$), as did HCHO, TVOC and CO_2, whereas CO did not (Table 7). Day 2 was the highest for these pollutants and was also the warmest and driest day (32.2 °C; 38.0% relative humidity). For $PM_{2.5}$, Day 2 differed from Day 1 (Holm $p = 0.012$) and Day 3 ($p = 0.007$), whereas Days 1 and 3 did not differ ($p = 0.073$). The difference between the highest and lowest day (12.9 µg/m^3, about 22% of the lowest) was modest compared with the spatial and time-of-day differences. At the fenceline, mean $PM_{2.5}$ was 102.3, 123.3 and 92.7 µg/m^3 on Days 1 to 3, and at E it was 35.3, 39.3 and 29.3 µg/m^3. $H0_{2a}$ was therefore rejected for all parameters, and $H0_{2\beta}$ for all parameters except CO.

Table 7: Variation in air-quality parameters across sampling days, based on mean values across all locations and sampling periods (Friedman test, df = 2, 15 blocks)

Parameter	Day 1	Day 2	Day 3	χ^2	p	W
$PM_{2.5}$ (µg/m^3)	63.3	71.4	58.5	14.52	< 0.001	0.48
HCHO (mg/m^3)	0.044	0.048	0.043	6.31	0.043	0.21
TVOC (mg/m^3)	0.112	0.121	0.110	10.47	0.005	0.35
CO (ppm)	1.9	2.1	1.7	3.43	0.180	0.11
CO_2 (ppm)	471.6	488.6	472.5	10.53	0.005	0.35
Temperature (°C)	31.2	32.2	31.1	11.14	0.004	0.37
Relative humidity (%)	41.9	38.0	41.7	11.82	0.003	0.39

Concurrent temperature and humidity

Across all 45 readings, $PM_{2.5}$ was positively associated with concurrent temperature (Spearman ρ = 0.39, p = 0.008) and negatively with relative humidity (ρ = −0.33, p = 0.026), and HCHO showed similar associations (ρ = 0.47 and −0.38). Because temperature and humidity vary with time of day and with the day, these associations largely restate the diurnal and day-to-day patterns above and are descriptive only.

Discussion

The spatial gradient and the extent of the facility's influence

All five measured parameters declined with increasing distance from the fenceline. This spatial pattern is consistent with the expected dispersion behaviour of pollutants from a ground-level industrial source. For $PM_{2.5}$, which separated the locations most clearly, nearly three-quarters of the total decline had occurred within 500 m. The result agrees in direction with studies around other facilities that handle mineral raw materials. In the Castellón ceramic cluster of eastern Spain, industrial–urban and rural stations behaved differently, and anthropogenic activity largely determined particulate levels (Vicente et al., 2011). In the Brazilian ceramic district studied by Mizutani et al. (2023), the ratio of mean PM_{10} between the most and least exposed towns was about 2.6, of the same order as the ratio of 3.1 between the fenceline and the comparison location here, although the size fraction, averaging time and instrument differ and the figures are not strictly comparable. In the Sharada industrial area of Kano, PM_{10} rose from residential neighbourhoods to the industrial core; the industrial–residential difference was only borderline significant with five sites per group, a reminder that small samples limit what tests can show (Tafida & Gana, 2025).

Absolute levels vary widely among studies and should be compared cautiously. Mean $PM_{2.5}$ at the quarrying, milling and loading sites of a cement plant in Cross River State was 27.0–31.6 μg/m^3 (Nwogu et al., 2025), similar to the level at the comparison location here and well below the fenceline mean. At the other end of the range, Taghizadeh et al. (2023) reported a highest mean $PM_{2.5}$ of about 13 μg/m^3 around a tile and ceramic factory in Iran. The difference may reflect dust control, sampling distance, method and climate, but it shows that fine-particle exposure near tile plants is not uniformly high; the Kachi fenceline values point to site-specific emission and control conditions.

The pairwise tests indicate that elevated concentrations were detectable to at least 100 m for every parameter, to 500 m for all except CO, and to about 1 km for $PM_{2.5}$, TVOC and, marginally, HCHO (adjusted p = 0.039). The failure to distinguish CO and CO_2 at 1 km, and CO at 500 m, from the comparison location should not be read as proof of no effect, because each comparison rests on nine paired readings and CO is reported in whole ppm; the concentrations at 1 km were numerically higher, and CO at E was at the lowest value the monitor reports. The practical implication is that residents within roughly 1 km of the facility are the most likely to be affected, which is consistent with the finding of more respiratory symptoms within 1 km of a cement factory in Zambia (Nkhama et al., 2017). The present data cannot establish respiratory illness among Kachi residents.

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The background also needs context. The mean at the comparison location (34.67 µg/m^3) is above the WHO 24-hour guideline value of 15 µg/m^3 (WHO, 2021), lower than the Harmattan-season $PM_{2.5}$ of 90–270 µg/m^3 reported in ground-based measurements in Kano and higher than the rainy-season values of 6.59–15.42 µg/m^3 reported in the same study (Idris et al., 2025). All 45 readings exceeded 15 µg/m^3, and 36 of 45 exceeded the 37.5 µg/m^3 interim target value (WHO, 2021). These comparisons are indicative only, because the guideline refers to 24-hour means and the readings are spot measurements. The highest HCHO reading (0.079 mg/m^3) was below the WHO 30-minute guideline value of 0.1 mg/m^3 (WHO, 2010), and the highest CO readings (4 ppm, about 4.6 mg/m^3) were below the WHO 8-hour value of 10 mg/m^3 (WHO, 2021), although the latter is an averaging-period comparison that spot readings cannot capture. Given the high regional background reported across sub-Saharan Africa (Awokola et al., 2022), the contribution of the facility, if any, is best described as a local increment on top of an already elevated regional level.

Possible sources of the pollutant gradients

The specific sources of $PM_{2.5}$ emissions within the facility were not documented during the study. Plausible contributors are material handling, cutting and finishing, stockpiles and residues, heavy-vehicle movement and resuspension of dust from unpaved surfaces, and combustion from vehicles, loaders and generators. $PM_{2.5}$ is a size fraction and not a chemical composition, so the monitor cannot show whether the particles contain crystalline silica or metals, which matter for health (Mizutani et al., 2023; Pope & Dockery, 2006).

Formaldehyde and TVOC followed the same distance pattern with different strength (about 1.9-fold and 3.0-fold between A and E). Sources could include fuel combustion in kilns, dryers and generators, vehicle exhaust and, if ceramic processes are involved, thermal breakdown of organic additives, binders and decoration materials, releasing aldehydes when fired (Ferrari & Zannini, 2017). Whether such materials are used at Kachi must be established from facility records. Formaldehyde is a sensory irritant (Salthammer et al., 2010) that also arises from combustion and from atmospheric oxidation of other volatile organic compounds, which can result in a non-zero reading at the comparison location. The HCHO and TVOC sensors respond to groups of compounds, so these values are screening indicators; regulatory use would require confirmation by sorbent-tube or canister sampling with laboratory analysis.

The finding that CO, CO_2 and $PM_{2.5}$ all rise towards the facility is consistent with a common combustion or thermal-process contribution. CO is a product of incomplete combustion that reduces oxygen delivery by binding to haemoglobin (Raub et al., 2000), but concentrations here were low. CO_2 is used here as an indicator of combustion and local atmospheric variation, not as a hazard in the sense of the other parameters: all values were far below the 1,000 ppm benchmark used by Nwogu et al. (2025), and the fenceline mean of 529 ppm is very close to the 528.3 ppm reported at the milling site of the Cross River cement plant. Adeniran et al. (2019) found 24-hour CO and volatile organic compounds within limits at all fenceline locations of a Nigerian cement complex, which, taken with the present results, suggests that for mineral-processing plants fine particles, rather than organic gases and CO, are likely the main concern. Monitoring location strongly influences measured concentrations: substantially higher CO levels have been reported within the production

area of a cement plant (Nwogu et al., 2025), whereas the present study measured concentrations at the fenceline and at receptor locations outside it, so the two sets of values are not directly comparable.

The afternoon maximum

Temporal variation was as pronounced as the spatial variation. All parameters were highest in the afternoon, and the morning-to-afternoon increase in $PM_{2.5}$ at the fenceline (48.4 µg/m^3) was about four times that at the comparison location (11.4 µg/m^3). This indicates that the afternoon peak had a local component in addition to any regional daily cycle that also affected E. It is not the usual urban pattern in sub-Saharan Africa, where $PM_{2.5}$ commonly peaks twice a day, at about 06:00 and 18:00, a pattern attributed to rush-hour traffic (Awokola et al., 2022). The Kachi pattern, lowest in the morning and highest in the afternoon, is more consistent with a daytime source, such as production, loading, heavy-vehicle movement and resuspension of dust from unpaved surfaces in hot, dry afternoon conditions. Poor dispersion is unlikely to explain the peak, because the atmospheric boundary layer is normally deepest and dispersion best in the afternoon. A humidity artefact is also unlikely: for the optical sensor type studied, readings overestimate reference $PM_{2.5}$ more at higher humidity (Barkjohn et al., 2021), whereas the afternoon maximum occurred at the lowest humidity. This reasoning applies to the sensor type studied and not necessarily to the monitor used here.

Two caveats apply. Temperature, humidity and many pollutants share a daily cycle, and most of the correlation of $PM_{2.5}$ with temperature and humidity arises from covariation with weather systems and not from direct dependence (Tai et al., 2010, 2012), so the association found in Section 3.5 does not mean that temperature or humidity caused the afternoon peak. Furthermore, because the facility's operating hours, traffic intensity and wind conditions were not documented, the observed afternoon peak could not be directly linked to any specific operational or external activity. In relative terms the morning-to-afternoon increase at 1 km (58%) was similar to that at the fenceline (57%), so the larger absolute increase near the source is the more informative indicator of a local contribution.

Day-to-day variation and seasonal context

Although statistically significant differences were observed among sampling days, their magnitude was modest compared with the spatial and diurnal variations. Day 2 recorded the highest concentrations of $PM_{2.5}$, HCHO, TVOC and CO_2 and was also the warmest and driest sampling day. These findings highlight the potential variability in operational and meteorological conditions, even within a three-day monitoring period. Longer records show how large such variation can be: Nwogu et al. (2025), sampling monthly through 2023 at a Nigerian cement plant, found significant month-to-month differences for several pollutants, and the dry-season to rainy-season contrast in Nigerian $PM_{2.5}$ is larger still (Awokola et al., 2022; Idris et al., 2025). These measurements were made late in the rainy season. Harmattan dust can raise concentrations across a whole monitoring area (Idris et al., 2025), so the gradient measured here may differ in the dry season, when a widespread increase would also lift the comparison location and could narrow the contrast with the facility.

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Conclusion

Around the tile manufacturing facility in Kachi Town, concentrations of $PM_{2.5}$, HCHO, TVOC, CO and CO_2 were highest at the fenceline and fell with distance to a comparison location 2 km away, while temperature and humidity did not differ among locations. All five parameters were significantly higher than at the comparison location at the fenceline (0 m) and 100 m, all except CO were higher at 500 m, and $PM_{2.5}$, TVOC and (marginally) HCHO were still higher at 1 km. All parameters also varied significantly with time of day and were highest in the afternoon, with an afternoon increase in $PM_{2.5}$ that was about four times larger at the fenceline than at the comparison location; differences between days were smaller. These patterns are consistent with a local source at the facility, with the greatest influence close to the plant in the afternoon, superimposed on an already elevated regional background. The study is limited by the absence of recorded sampling coordinates, wind and production data, the use of a single uncalibrated portable monitor over three days in one season, and repeated measurements that are not independent. Calibrated, wind-resolved and seasonal monitoring is therefore needed to confirm attribution. Meanwhile, dust control at source should be reinforced, including covering stockpiles and material transfer points, wetting or paving unpaved roads and yards, and maintaining dust collection on equipment. New sensitive land uses such as homes, schools and clinics should be avoided within about 1 km of the facility until wind-resolved monitoring defines a firmer distance. Finally, the composition of the particles, including respirable crystalline silica, should be measured, and monitoring should be combined with a health survey of residents and workers to link exposure to symptoms.

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