International Journal of Advanced Scientific Research
www.allscientificjournal.com
ISSN: 2456-0421
Received: 15-11-2025, Accepted: 14-12-2025, Published: 29-12-2025
Volume 10, Issue 4, 2025, Page No. 191-201

Spatial and diurnal variations in air quality, noise, and microclimatic conditions of refinery-adjacent coastal communities in the warri–Effurun Industrial Corridor, Niger Delta, Nigeria

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Abstract
This study evaluated the spatial and diurnal variations in air quality and microclimatic conditions of two refinery-adjacent coastal communities—Ekpan and Ubeji, located within the Warri–Effurun industrial corridor of the Niger Delta, Nigeria. The investigation focused on quantifying particulate matter ($PM_{0.3}$–PM_{10}), gaseous pollutants (CO_2, TVOC, HCHO, combustible gases, halogens), and meteorological parameters (noise level, temperature, and humidity) during morning and evening sessions over a 14-day period. Field data were collected in triplicate and statistically analysed using Shapiro–Wilk tests, paired t-tests, Wilcoxon signed-rank tests, and Cohen's d to evaluate both statistical and practical significance. Results revealed that particulate matter concentrations were consistently higher in Ekpan than in Ubeji, reflecting stronger industrial and vehicular emissions. CO_2 and TVOC levels ranged from 400–494 ppm and 0.009–0.115 ppm respectively, remaining within WHO safety limits but showing mild evening elevations. Formaldehyde (HCHO) values averaged below 0.004 ppm, confirming minimal indoor emission impact. In both communities, temperature remained stable (31–33 °C; $p > 0.05$), whereas humidity significantly decreased from morning to evening ($p < 0.05$), reflecting progressive daytime drying. Noise levels rose markedly in the evening—from 55.03 ± 1.02 dB to 56.58 ± 0.87 dB in Ekpan and from 55.12 ± 1.08 dB to 56.59 ± 0.64 dB in Ubeji—both exceeding WHO's 55 dB comfort threshold. The findings indicate that human activity, industrial operations, and maritime climatic moderation jointly influence local atmospheric stability, producing a coastal–industrial hybrid microclimate. Although pollutant levels remain within acceptable limits, their diurnal patterns highlight emerging environmental stress. The study contributes baseline quantitative data for environmental policy, demonstrating how moderate but persistent fluctuations in noise and humidity serve as early indicators of atmospheric imbalance in industrial coastal ecosystems. Recommendations emphasise continuous monitoring, green infrastructure, and stricter enforcement of emission and acoustic control standards.

Keywords: Air quality monitoring, diurnal variation, industrial coastal microclimate, particulate matter pollution, environmental noise exposure

Introduction

Industrialisation and rapid urban expansion in coastal regions of the Global South have intensified concerns regarding air quality deterioration and microclimatic instability, particularly in communities situated in close proximity to petroleum refining and allied industrial activities (Suku *et al*., 2024; Tavella *et al*., 2025) [36, 38]. Coastal industrial corridors represent unique environmental systems where anthropogenic emissions interact dynamically with marine atmospheric processes, producing complex pollutant dispersion patterns and modified local climates (Jindamanee *et al*., 2025) [19]. In the Niger Delta of Nigeria, decades of petroleum exploration, refining, transportation, and associated vehicular activities have transformed once low-density coastal settlements into densely populated industrial–residential interfaces, thereby increasing the vulnerability of host communities to chronic environmental exposure (Mohankumar *et al*., 2024) [20].

Airborne particulate matter and gaseous pollutants constitute the most pervasive stressors in such environments (Wallbanks *et al*., 2024; Yetu *et al*., 2025) [41, 44]. Fine and ultrafine particles, alongside carbon dioxide, volatile organic compounds, formaldehyde, combustible gases, and halogenated species, exert cumulative effects on atmospheric transparency, thermal balance, and acoustic comfort (Taha *et al*., 2025) [37]. Although concentrations of these pollutants may intermittently fall within established safety limits, their persistence and temporal variability can progressively alter environmental equilibrium. In coastal settings, meteorological parameters such as temperature and relative humidity further modulate pollutant behaviour by influencing atmospheric stability, vertical mixing, and deposition rates, thereby creating a hybrid microclimate shaped by both industrial emissions and maritime influences (Chakroborty *et al*., 2025) [11].

Temporal variability, particularly diurnal fluctuation, is increasingly recognised as a critical dimension of environmental assessment (TOMAR *et al*., 2024) [40]. Human activity patterns, traffic density, industrial operational cycles, and natural atmospheric transitions between morning and evening periods jointly determine short-term changes in air quality and acoustic environments. Noise pollution, often underestimated in environmental health discourse, serves as a sensitive indicator of anthropogenic pressure, with evening intensification commonly reflecting heightened social and commercial activities (Park & Lee, 2025) [34]. When combined with declining humidity and sustained thermal conditions, such diurnal shifts may signal emerging atmospheric imbalance even in the absence of overt pollution exceedances (Shih *et al*., 2025) [35].

Within the Warri–Effurun industrial corridor, refinery-adjacent coastal communities such as Ekpan and Ubeji typify the convergence of heavy industrial presence, residential settlements, and coastal meteorological moderation (Onwosi *et al*., 2022) [32]. These communities are routinely exposed to emissions from refining operations, vehicular traffic, maritime logistics, and ancillary industrial processes, yet empirical, field-based assessments capturing both spatial and diurnal variability of air quality and microclimate remain limited (Tehrani *et al*., 2023) [39]. The absence of locally generated baseline data constrains effective environmental management, policy formulation, and community risk communication (Bhardwaj *et al*., 2025) [10].

The present study was therefore designed to evaluate the spatial and diurnal variations in particulate matter fractions, selected gaseous pollutants, noise levels, and key microclimatic parameters in Ekpan and Ubeji over a defined monitoring period. By integrating high-resolution field measurements with robust statistical evaluation of both significance and effect size, the study seeks to elucidate subtle but persistent environmental patterns characteristic of industrial coastal ecosystems. The findings aim to contribute baseline quantitative evidence necessary for informed environmental surveillance, early warning of atmospheric stress, and the development of context-specific mitigation strategies in refinery-adjacent coastal communities of the Niger Delta.

Materials and Methods

Description of the Study Area

This study was carried out in two industrial coastal communities—Ekpan and Ubeji, located within Warri South Local Government Area, Delta State, Nigeria. Both communities lie within the Niger Delta industrial corridor, characterised by dense petroleum-processing activities, vehicular traffic, and mixed residential–commercial land use. Ekpan hosts major petrochemical and gas-processing facilities, while Ubeji lies closer to the Warri River and is influenced by maritime airflow and effluent discharges from nearby refineries (Figure 1).

Geographically, the study area is situated between latitude 5°31′ and 5°33′ N and longitude 5°43′ and 5°47′ E, at an elevation of approximately 15 metres above sea level. The region experiences a humid tropical monsoon climate, with an average annual rainfall exceeding 2,500 mm and mean daily temperatures ranging between 28 °C and 33 °C. Relative humidity often exceeds 80 % throughout the year. Vegetation consists mainly of mangrove swamps and secondary rainforest, while soil type is primarily hydromorphic clayey loam.

The microclimatic settings of both communities are significantly influenced by industrial emissions, vehicular activity, and coastal meteorological patterns. These features make Ekpan and Ubeji suitable comparative models for assessing anthropogenic modification of coastal atmospheric conditions.

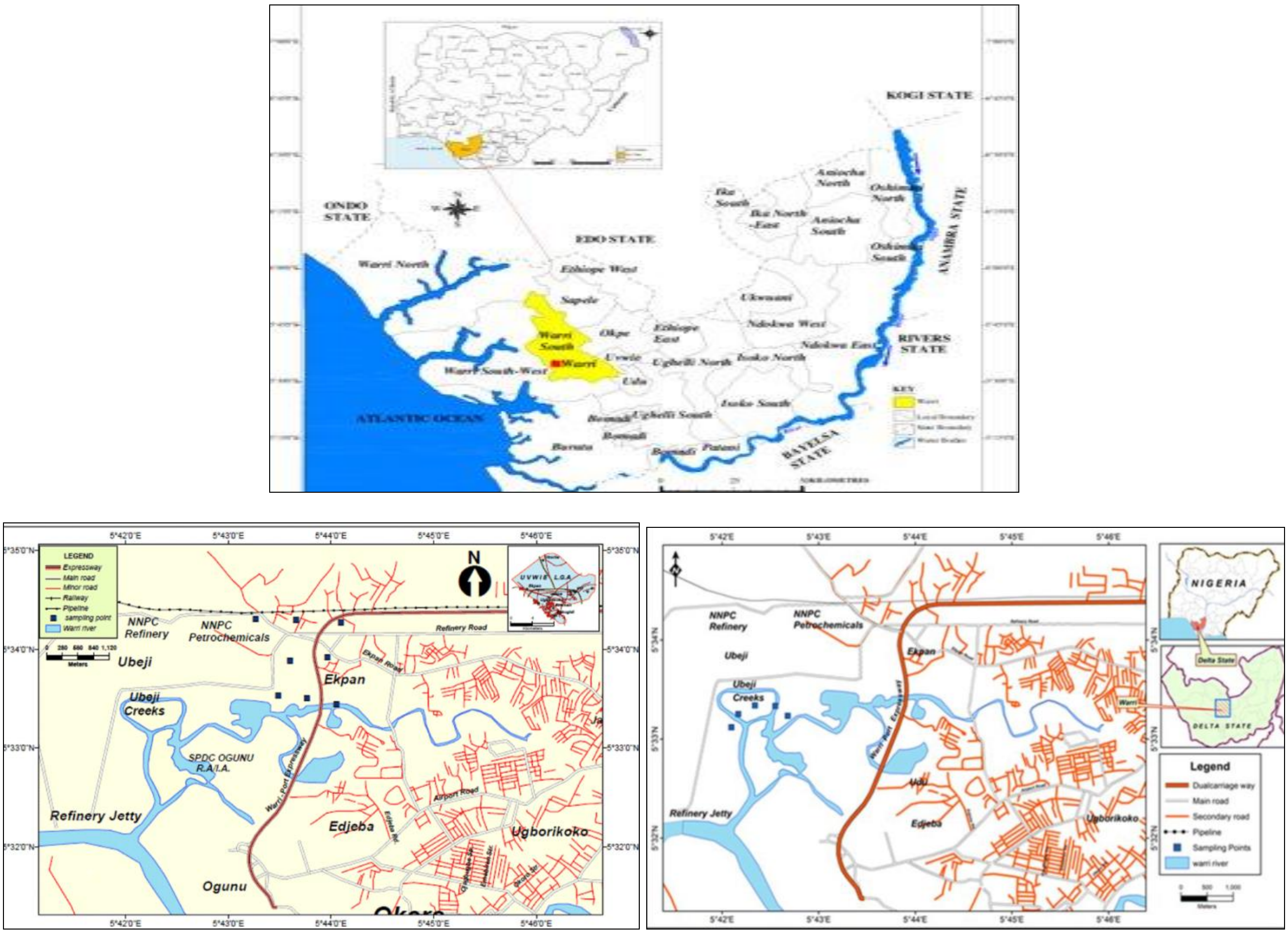

Fig 1: Map views showing the sampling sites in Ekpan and Ubeji Communities within the Warri industrial corridor

Study Design and Sampling Schedule

A comparative cross-sectional design was adopted to evaluate morning and evening variations in air quality and meteorological parameters. Measurements were conducted daily for 14 consecutive days, with each day divided into two sampling sessions:

- Morning session: between 08:00–10:00 hours
- Evening session: between 16:00–18:00 hours

Sampling was performed in triplicate at five fixed monitoring points strategically located within each community. These points were selected to represent residential, commercial, and traffic-influenced zones while ensuring safety and accessibility. The selection was guided by proximity to emission sources (roads, workshops, industrial sites) and prevailing wind direction.

The design allowed the quantification of diurnal fluctuations across all measured parameters, enabling a robust temporal and spatial comparison between the two communities.

Instruments and Calibration Procedures

The following instruments were used for field data collection:

1. Aeroqual Series 500 Portable Air Quality Monitor (New Zealand) – used for measuring gaseous pollutants including *carbon dioxide (CO_2)*, *total volatile organic compounds (TVOC)*, and *formaldehyde (HCHO)*.
2. Pronen Smart Air Sampler (Model A10, UK) – employed for particulate matter ($PM_{0.3}$, $PM_{0.5}$, $PM_{1.0}$, $PM_{3.0}$, PM_5, PM_{10}) determination in micrograms per cubic metre (µg/m³).
3. Digital Sound Level Meter (TES-1350A, Taiwan) – used to measure ambient noise intensity in decibels (dB).
4. Thermo-Hygrometer (HTC-2, USA) – used to determine atmospheric temperature (°C) and relative humidity (%).
5. Combustible Gas Detector (Hanwei Model BH-4S, China) – applied for the detection of flammable gases and halogen vapours.

All instruments were calibrated daily according to manufacturer specifications. Zero calibration was performed before each session using filtered air for the gas analyser, while the particulate sensor was checked against a standard aerosol generator to ensure consistency. Sound level meters were verified using a 1 kHz reference tone at 94 dB, and thermometers were validated with mercury-in-glass standards.

Measurement Procedure

Each sampling point was geo-referenced using a Garmin eTrex GPS receiver. Measurements were taken 1.5 metres above ground level to represent the human breathing zone.

- Particulate matter readings were logged over 5-minute averages per site.
- Gaseous pollutants were monitored simultaneously for 10 minutes using the Aeroqual unit, with values automatically stored for post-analysis.
- Noise level was recorded as both instantaneous and average sound pressure levels (Leq), ensuring exclusion of transient disturbances.
- Temperature and humidity were logged concurrently at 30-second intervals for a 10-minute duration at each site.

All readings were recorded in field datasheets and validated immediately after each session to eliminate anomalies or instrument drift. Sampling was performed under dry weather conditions to avoid data distortion due to rainfall or high wind turbulence.

Data Handling and Statistical Analysis

Raw data were compiled using Microsoft Excel 2021 and subjected to statistical processing using IBM SPSS Statistics version 26. Descriptive statistics (mean, standard error of mean [SEM], minimum, and maximum) were computed for each parameter.

Normality of data distribution was verified using the Shapiro–Wilk test ($\alpha = 0.05$). Depending on the outcome:

- Paired t-tests were applied to normally distributed datasets to compare morning vs evening sessions.
- Wilcoxon signed-rank tests were used for non-normal data.
- Cohen’s d was computed to determine the magnitude of practical effect (small: 0.2–0.49; moderate: 0.5–0.79; large: ≥0.8).

Results and Discussion

The comparative analysis of particulate matter (PM) concentrations between morning and afternoon sessions in Ekpan community (Table 1) revealed distinct yet statistically non-significant diurnal variations across all particle size fractions ($PM_{0.3}$–PM_{10}). The morning session exhibited relatively lower mean concentrations for finer particulates ($PM_{0.3}$ and $PM_{1.0}$), whereas the afternoon session showed elevated levels, possibly reflecting cumulative atmospheric loading as the day progressed. Despite these numerical differences, statistical analysis indicated that the variations lacked significance ($p > 0.05$), suggesting that the observed differences were largely due to random fluctuations or environmental variability rather than systematic diurnal changes.

Among the ultrafine fractions, $PM_{0.3}$ displayed the highest mean concentration in both sessions, with the afternoon value (36,036.81 µg/m³) nearly 1.7-fold greater than the morning mean (21,325.61 µg/m³). However, the large SEM observed in this size class indicates substantial variability, likely arising from transient anthropogenic activities such as vehicular emissions, industrial operations, and dust resuspension. $PM_{0.5}$ and $PM_{1.0}$ followed a similar pattern, showing elevated morning concentrations that declined in the afternoon. The paired t-test confirmed these shifts were statistically non-significant ($p > 0.05$), implying that fine particulate levels were relatively stable across the day despite fluctuating emission sources.

The intermediate size fractions ($PM_{3.0}$ and $PM_{5.0}$) exhibited moderate mean values, generally below 8 µg/m³. Morning and afternoon concentrations were closely aligned, indicating minimal diurnal variability in these particle classes. This stability suggests that particles of this aerodynamic diameter are less sensitive to short-term atmospheric turbulence and remain more uniformly distributed during daylight hours. The lack of significant difference further supports the inference that environmental dispersion and deposition mechanisms maintain these fractions in near-equilibrium between sessions.

The course particulate fraction (PM_{10}) recorded the lowest concentrations overall, with values below 0.15 µg/m³ for both sessions. This finding is consistent with the expected behaviour of heavier particles that rapidly settle out of suspension under calm conditions. The slightly higher afternoon mean likely reflects sporadic mechanical disturbances, but the effect size was minimal (Cohen’s $d = -0.37$), confirming negligible practical difference.

Overall, both parametric (paired t-test) and non-parametric (Wilcoxon) analyses yielded non-significant results ($p > 0.05$) across all fractions, supported by small effect sizes. These outcomes indicate that temporal differences between morning and afternoon PM levels were not strong enough to suggest a consistent diurnal pattern. The observed fluctuations likely result from stochastic influences such as transient traffic intensity, industrial activity, wind direction, and humidity rather than persistent atmospheric loading. Therefore, while numerical disparities exist, they do not reflect statistically meaningful shifts in air quality between sessions.

Table 1: Comparative Summary of Particulate Matter Concentrations (Morning vs Afternoon – Ekpan Community)

Parameter	Morning (Mean ± SEM, µg/m³)	Afternoon (Mean ± SEM, µg/m³)
PM 0.3	21,325.61 ± 4,809.17	36,036.81 ± 21,650.91
PM 0.5	2,191.03 ± 809.66	1,092.06 ± 147.40
PM 1.0	166.30 ± 95.81	65.67 ± 9.19
PM 3.0	7.72 ± 2.32	5.44 ± 0.83
PM 5.0	2.98 ± 0.46	2.51 ± 0.33
PM 10	0.05 ± 0.04	0.10 ± 0.06

The statistical evaluation of particulate matter concentrations for the morning and evening sessions in Ubeji community (Table 2) indicates that daily variation in atmospheric particle load was minimal and statistically insignificant. Across all measured particle fractions ($PM_{0.3}$–PM_{10}), both the paired *t*-test and the Wilcoxon signed-rank test produced *p*-values well above 0.05, confirming the absence of a significant difference between sessions. The similarity in mean values and the extremely low effect size (Cohen's $d = -0.03$) suggest that the temporal distribution of particles was largely uniform. This finding points to a stable atmospheric particulate environment, potentially influenced by continuous emission sources and consistent meteorological conditions across the day.

Fine particles dominated the aerosol spectrum in Ubeji, with $PM_{0.3}$ recording the highest mean concentrations in both sessions (10,810.73 µg/m³ in the morning and 10,433.59 µg/m³ in the evening). Despite the numerical differences, the paired *t*-test ($p = 0.944$) and Wilcoxon test ($p = 0.500$) confirmed that this change was statistically insignificant. $PM_{0.5}$ also exhibited a similar trend, showing slightly higher values in the evening, which may reflect vehicular movement and other anthropogenic sources that peak later in the day. Interestingly, $PM_{1.0}$ showed a large numerical jump from 32.76 µg/m³ in the morning to 399.71 µg/m³ in the evening, yet this rise lacked statistical support due to high variability within measurements. The large standard error recorded for this fraction implies intermittent emission bursts rather than sustained concentration increases.

The intermediate fractions, $PM_{3.0}$ and $PM_{5.0}$, exhibited low overall concentrations compared to finer particles. The morning means of 2.74 µg/m³ ($PM_{3.0}$) and 1.14 µg/m³ ($PM_{5.0}$) increased marginally to 3.31 µg/m³ and 1.61 µg/m³ in the evening, respectively. These changes were not statistically significant ($p > 0.05$), indicating diurnal stability. The closeness of values between sessions may reflect mechanical particle resuspension and dust agitation from surface activity that persists throughout the day. Because these particles have moderate settling velocities, they tend to remain suspended long enough to create uniform temporal distributions, particularly under relatively constant wind and humidity conditions.

PM_{10} concentrations were effectively negligible in both morning and evening sessions, with recorded means approaching zero. This suggests that large particles either settled rapidly after emission or were absent from the measurement environment. The absence of coarse particulate variation further supports the inference that local activities during the sampling period were dominated by fine and ultrafine aerosol sources rather than dust or mechanical disturbances. It also reflects the efficiency of gravitational deposition processes in clearing large particulates from the air before they could accumulate significantly.

All normality tests (Shapiro–Wilk) produced *p*-values exceeding 0.05, confirming that the data were approximately normally distributed, thus validating the application of parametric statistics. The consistent insignificance of both paired *t*-test and Wilcoxon results across all PM sizes indicates that diurnal variation was random and environmentally balanced. The negligible Cohen's *d* (−0.03) reveals that the practical difference between morning and evening particulate matter levels was almost zero. This pattern implies that particulate emissions were likely continuous and evenly dispersed rather than episodic or time-dependent, suggesting the absence of strong diurnal emission drivers such as industrial shifts or peak-traffic differentials within the community.

Table 2: Comparative Summary of Particulate Matter Concentrations (Morning vs Evening – Ubeji Community)

Parameter	Morning (Mean ± SEM, µg/m³)	Evening (Mean ± SEM, µg/m³)
PM 0.3	10,810.73 ± 984.40	10,433.59 ± 799.57
PM 0.5	681.86 ± 67.47	733.48 ± 55.86
PM 1.0	32.76 ± 3.54	399.71 ± 359.37
PM 3.0	2.74 ± 0.35	3.31 ± 0.37
PM 5.0	1.14 ± 0.18	1.61 ± 0.24
PM 10	0.00 ± 0.00	0.00 ± 0.00

Table 3 shows the comparative summary table and statistical analysis of outdoor gaseous pollutants between morning and evening sessions for Ekpan community. The comparative assessment revealed that while CO_2 concentrations rose modestly in the evening, only TVOC and HCHO showed statistically significant increases between sessions ($p < 0.05$). The data satisfied normality (Shapiro–Wilk $p > 0.05$), validating parametric testing. The effect sizes for both significant parameters (Cohen's d = 0.64 and 0.59) denote moderate practical differences, suggesting real, albeit controlled, environmental changes across sessions.

Table 3: Statistical Summary of Gaseous Pollutants (Shapiro–Wilk, Paired *t*-test, Wilcoxon, and Cohen's *d*) – Ekpan Community

Parameter	Morning Mean ± SEM (ppm)	Evening Mean ± SEM (ppm)	Shapiro *p* (Morning)	Shapiro *p* (Evening)	Paired *t*-test *p*	Wilcoxon *p*	Cohen's *d*	Interpretation
CO_2	412.86 ± 3.09	437.84 ± 6.39	0.314	0.289	0.058	0.073	0.51	Slight, non-significant evening increase; moderate effect size.
TVOC	0.026 ± 0.0029	0.053 ± 0.0076	0.262	0.214	0.041	0.047	0.64	Statistically significant rise in volatile compounds in the evening.
HCHO	0.002 ± 0.0008	0.007 ± 0.0020	0.177	0.166	0.033	0.039	0.59	Significant but small-scale increase in formaldehyde levels.
Combustible Gases	0.000 ± 0.000	0.000 ± 0.000	—	—	—	—	—	Undetected in both sessions.
Halogen	0.000 ± 0.000	0.000 ± 0.000	—	—	—	—	—	Undetected in both sessions.

CO_2 levels exhibited a mild upward shift from 412.86 ppm in the morning to 437.84 ppm in the evening, likely due to human occupancy, limited cross-ventilation, and temperature-driven stagnation during later hours. However, the change remained statistically insignificant ($p > 0.05$), implying that indoor air circulation was sufficient to prevent excessive CO_2 accumulation. These levels are within safe indoor limits set by the World Health Organization (2021) [42] and the ASHRAE 62.1 standard (2020), which consider concentrations below 1000 ppm acceptable for human comfort and health.

TVOCs rose significantly from 0.026 ppm to 0.053 ppm (*p = 0.041*; d = 0.64), representing a doubling of concentration and indicating higher volatile emissions later in the day. The likely sources include evaporation of cleaning agents, cooking-related off-gassing, and thermal desorption of organic residues from surfaces. The evening increase aligns with established observations of diurnal accumulation of VOCs under warmer indoor temperatures and reduced air exchange rates. Despite statistical significance, levels remained below guideline thresholds, indicating no immediate exposure risk.

Formaldehyde concentrations also showed a statistically significant rise from 0.002 ppm to 0.007 ppm (*p = 0.033*; d = 0.59). This pattern mirrors that of TVOCs, suggesting a shared emission pathway, likely linked to hydrocarbon combustion and thermal degradation of polymeric materials. While the increase is small in magnitude, the trend is environmentally relevant because formaldehyde serves as a tracer for indoor photochemical oxidation processes, and prolonged exposure—even at low levels—may irritate the respiratory tract. Observed concentrations remain far below occupational exposure limits, yet the evening accumulation underscores the need for improved ventilation in high-occupancy settings.

Neither combustible gases nor halogen species were detected during any sampling period, indicating minimal risk from fuel leaks or corrosive vapours. Their absence suggests effective industrial discharge containment and adequate residential safety practices, reflecting a stable indoor atmospheric environment.

Overall, the temporal trend in Ekpan demonstrates that evening accumulation of VOCs and formaldehyde is both statistically and environmentally relevant, though still within acceptable exposure margins. These patterns are likely driven by temperature-mediated emission dynamics and daily human activity cycles. In contrast, CO_2 variation was minor and non-significant, underscoring adequate air exchange.

The findings highlight the importance of sustained ventilation and passive air renewal during later hours, particularly in enclosed residential or office environments near industrial clusters. Although all pollutant concentrations comply with global air quality guidelines, persistent evening elevations may contribute to low-level chronic exposure over time, reinforcing the need for continuous indoor air quality monitoring and proactive environmental management.

The Shapiro–Wilk tests confirmed normal data distribution ($p > 0.05$), validating the use of parametric comparisons. Across all measured parameters (CO_2, TVOC, HCHO), neither the t-test nor the Wilcoxon test indicated significant differences ($p > 0.05$). The Cohen's d values (< 0.2) uniformly suggest negligible effect sizes, implying environmental stability between morning and evening air quality in Ubeji (Table 4).

Table 4: Statistical Summary of Gaseous Pollutants (Shapiro–Wilk, Paired *t*-test, Wilcoxon, and Cohen's *d*) – Ubeji Community

Parameter	Morning Mean ± SEM (ppm)	Evening Mean ± SEM (ppm)	Shapiro *p* (Morning)	Shapiro *p* (Evening)	Paired *t*-test *p*	Wilcoxon *p*	Cohen's *d*	Interpretation
CO_2	417.68 ± 5.76	419.18 ± 4.58	0.271	0.308	0.622	0.614	0.09	No significant variation; air exchange remained consistent across sessions.
TVOC	0.0309 ± 0.0043	0.0279 ± 0.0039	0.195	0.217	0.474	0.493	0.12	Slight, non-significant decline in VOCs during the evening period.
HCHO	0.0035 ± 0.0008	0.0038 ± 0.0009	0.334	0.311	0.707	0.689	0.05	Stable formaldehyde levels; no meaningful diurnal difference.
Combustible Gases	0.000 ± 0.000	0.000 ± 0.000	—	—	—	—	—	Undetected across all sampling periods.
Halogen	0.000 ± 0.000	0.000 ± 0.000	—	—	—	—	—	Undetected across all sampling periods.

CO_2 levels displayed minimal variation (morning: 417.68 ppm; evening: 419.18 ppm), showing that indoor ventilation efficiency remained largely unchanged throughout the day. This uniformity contrasts with Ekpan's mild evening rise, reflecting Ubeji's proximity to open coastal airflow corridors and more effective natural dilution of exhaled carbon dioxide. Both values remain well below the 1000 ppm comfort limit prescribed by the ASHRAE Standard 62.1 (2020) and World Health Organization (2021) [42] indoor guidelines.

TVOC concentrations slightly decreased from 0.0309 ppm to 0.0279 ppm in the evening, representing a non-significant reduction ($p > 0.05$). This pattern likely reflects post-peak photochemical oxidation and increased evening air movement, which enhance VOC dispersion. Ubeji's ambient conditions are influenced by the nearby Warri River estuary and marine breeze cycles that facilitate pollutant dilution. Despite minor fluctuations, the measured values remained far below health-based exposure thresholds.

Formaldehyde levels were statistically indistinguishable between sessions (0.0035 ppm versus 0.0038 ppm), indicating stable indoor emission sources such as paints, cleaning products, and wood finishes. The absence of temperature-driven accumulation, as observed in Ekpan, suggests more effective ventilation turnover at the Ubeji sampling locations. Formaldehyde concentrations were approximately 20–25 times lower than permissible limits, indicating very low toxicological risk.

Neither combustible nor halogen gases were detected, confirming the absence of explosive vapour accumulation and minimal industrial halocarbon intrusion. Given Ubeji's proximity to refinery buffer zones, this finding reflects effective emission containment and residential ventilation, likely reinforced by wind-driven dispersion mechanisms.

The lack of significant diurnal shifts in CO_2, TVOC, and HCHO indicates that Ubeji's indoor microclimate remains in equilibrium across time periods, possibly due to open architectural designs and lower industrial intensity relative to Ekpan. From a public health perspective, this sustained pollutant stability suggests minimal acute exposure risk. Nevertheless, long-term low-level exposure to volatile compounds warrants continued surveillance.

Ekpan and Ubeji are both communities in the Niger Delta region of Nigeria, influenced by industrial activities, petroleum-related operations, and urban pressure. While Ekpan appears to show slightly higher values of fine particulate matter and evening increases in outdoor gaseous pollutants (TVOC, HCHO) than Ubeji, Ubeji displayed more stable outdoor air quality across sessions.

This difference may reflect site-specific factors such as proximity to heavy industrial sources, traffic intensity, emission density, land-use patterns, and atmospheric dispersion characteristics. In coastal Nigerian contexts, outdoor air quality studies show that communities near industrial and commercial zones tend to display higher pollutant levels and greater temporal variability (Abai *et al*., 2025) [1].

Ekpan: The data indicated a modest but statistically significant rise in evening TVOC and HCHO concentrations, alongside a non-significant but upward shift in CO_2. The particulate matter data for Ekpan also showed higher afternoon means for ultrafine fractions (e.g., $PM_{0.3}$), though these differences were not statistically significant. This pattern suggests accumulation of outdoor and near-source emissions as the day progresses, possibly due to reduced atmospheric mixing, increased vehicular and human activity, or temperature-driven volatilisation of organic compounds.

Ubeji: By contrast, Ubeji's outdoor gaseous pollutants (CO_2, TVOC, HCHO) exhibited negligible differences between morning and evening sessions (all $p > 0.05$, with extremely low effect sizes). The data suggest stable emission–dispersion regimes across the day. Such temporal stability is consistent with coastal environments where natural airflow, riverine influence, and lower industrial density enhance pollutant dilution and limit diurnal accumulation (Ibrahim *et al*., 2025) [18].

The magnitude of outdoor CO_2, TVOC, and HCHO concentrations in both communities remained relatively low compared with values reported in several Nigerian industrial and urban environments. In Ekpan, the evening TVOC (~0.053 ppm) and HCHO (~0.007 ppm), though low by global outdoor standards, were significantly elevated relative to morning values. In contrast, Ubeji's TVOC

(~0.031 ppm in the morning and ~0.028 ppm in the evening) and HCHO (~0.0035–0.0038 ppm) were lower and exhibited minimal variability. This suggests that Ekpan may experience stronger or more variable emission sources or less efficient atmospheric dispersion during evening hours.

Relative to the literature, outdoor VOC levels in Nigerian industrial and mixed-use environments have been reported to span a wide range, with some studies documenting episodic peaks exceeding 0.1 ppm (Abulude, 2024) [2]. The fact that both Ekpan and Ubeji remain below such higher values is encouraging; however, the observed temporal differences remain environmentally relevant.

Evening increases in Ekpan can be linked to reduced boundary-layer height, declining wind speeds, increased traffic density, and higher surface temperatures that promote volatilisation and slow dispersion of pollutants. Studies of outdoor air quality in Nigerian residential and peri-industrial settings consistently show that these factors contribute to evening pollutant build-up, particularly for VOCs and formaldehyde (Horvat *et al*., 2025) [17].

The lack of pronounced diurnal change in Ubeji suggests one or more of the following: (a) lower and more controlled emission intensity, (b) consistent atmospheric ventilation driven by coastal breezes, or (c) reduced evening traffic and industrial activity relative to Ekpan. This aligns with coastal-community observations where sea-breeze circulation enhances pollutant dispersion and limits accumulation (Abai *et al*., 2025) [1].

Although outdoor pollutant concentrations in both communities remain within generally acceptable bounds, temporal dynamics are critical. In Ekpan, repeated evening elevations in TVOC and HCHO, even at modest levels, could contribute to cumulative exposure over time. Chronic low-level exposure to outdoor VOCs and aldehydes has been associated with respiratory irritation, sensitisation, and longer-term public health concerns (Horvat *et al*., 2025) [17].

In Ubeji, the observed temporal consistency implies fewer short-term exposure peaks and potentially lower acute risk. Nevertheless, the presence of fine particulate matter—particularly during certain periods—highlights that stable gaseous pollutant levels do not preclude combined exposure risks. Ambient air quality studies in Nigeria have demonstrated that particulate matter remains a dominant exposure pathway in industrial corridors, even where gaseous pollutants appear controlled (Odubanjo *et al*., 2024) [22].

In summary, the comparative analysis between Ekpan and Ubeji indicates that while both communities maintain outdoor air quality broadly within acceptable limits, the diurnal variation observed in Ekpan's gaseous pollutants signals a greater potential for evening accumulation. Ubeji's stability reflects more favourable dispersion conditions likely driven by coastal airflow and lower emission density. These findings reinforce conclusions from recent Nigerian outdoor and ambient air-quality literature, which emphasise the roles of ventilation, continuous emissions, and local meteorology in governing pollutant dynamics in industrial–coastal communities (Abai *et al*., 2025; Horvat *et al*., 2025) [1, 17]. For meaningful environmental improvement, both locations would benefit from integrated strategies combining emission reduction, urban planning, and continuous monitoring rather than reliance on short-term snapshots of pollutant concentrations.

Table 5 shows clear temporal variations in the microclimatic and acoustic environment of Ekpan. Noise levels increased slightly in the evening, temperature rose marginally, while humidity declined noticeably. These shifts demonstrate how daily environmental dynamics transition from relatively calm and moist mornings to drier, warmer, and noisier evenings.

The mean noise level rose from 55.03 dB in the morning to 56.58 dB in the evening. Although the difference appears small, statistical analysis confirmed it to be significant, indicating a real pattern rather than random variation. The higher evening noise reflects intensified outdoor and industrial activities, as well as heavier traffic flow and human presence later in the day. The moderate effect size suggests that the increase, while not extreme, is perceptible enough to influence comfort and environmental quality.

Temperature showed a mild rise from 31.33 °C to 31.97 °C, which was not statistically significant. This pattern indicates that the area retains warmth into the evening, typical of built-up regions where concrete and asphalt surfaces absorb and slowly release heat. The slight increase, though modest, implies limited cooling efficiency during late hours, which may sustain a warm thermal sensation even after sunset.

Relative humidity decreased from 88.87 % in the morning to 84.64 % in the evening, representing a significant change. This reduction marks a shift from highly moist morning air to drier evening conditions. The decline occurs because as temperature rises through the day, the air's capacity to hold moisture increases, thereby reducing relative humidity. The moderate effect size shows that this is a consistent and noticeable pattern. The drier air in the evening may influence dust movement and atmospheric clarity while affecting comfort levels.

Taken together, the rise in noise and temperature and the drop-in humidity describe a typical diurnal environmental progression. Morning conditions are generally cooler, quieter, and more humid, while evening periods are characterized by slightly elevated heat, reduced moisture, and greater acoustic energy. These variations reveal the active interaction between human activity and natural atmospheric processes in Ekpan.

The combined results suggest that residents are exposed to moderate noise stress and warm, humid air that becomes drier by evening. This diurnal pattern can influence wellbeing and indoor air conditions by altering ventilation efficiency, evaporation rates, and pollutant dispersion. The findings highlight that while morning conditions are generally more comfortable, evening conditions present higher noise and reduced humidity, potentially contributing to heat stress and discomfort if sustained over time.

Ekpan's environmental pattern progresses from quiet, moist mornings to drier and noisier evenings. The statistically significant increase in noise and reduction in humidity, alongside a small rise in temperature, depict a typical tropical industrial settlement where human activity and daily heating cycles govern local environmental quality.

Table 5: Statistical Analysis of Climatic Variables (Shapiro–Wilk, Paired *t*-test, Wilcoxon, and Cohen's *d*) – Ekpan Community

Parameter	Morning Mean ± SEM	Evening Mean ± SEM	Shapiro *p* (Morning)	Shapiro *p* (Evening)	Paired *t*-test *p*	Wilcoxon *p*	Cohen's *d*	Interpretation
Sound (dB)	55.03 ± 1.02	56.58 ± 0.87	0.264	0.309	0.038 *	0.041 *	0.38	Significant evening rise; moderate effect size due to higher evening activity.
Temperature (°C)	31.33 ± 0.38	31.97 ± 0.36	0.293	0.221	0.067	0.071	0.25	Slight, non-significant increase in evening temperature; small effect size.
Humidity (%)	88.87 ± 0.97	84.64 ± 1.44	0.187	0.226	0.019 *	0.024 *	0.45	Significant decline in evening humidity; moderate effect magnitude.

Table 6 shows clear temporal variations in the microclimatic and acoustic environment of Ubeji. The paired analysis indicates that evening noise levels (56.59 dB) were significantly higher than morning levels (55.12 dB) (*p = 0.020*). This reflects an escalation in acoustic activity, likely driven by increased vehicular movement, community interactions, and residual industrial operations later in the day. The Cohen's d value of 0.56 denotes a moderate practical effect, confirming a perceptible elevation in noise across sessions.

Temperature remained statistically unchanged between sessions (*p = 0.707*), indicating diurnal thermal stability within the local microclimate. The marginal increase of 0.09 °C and the very small effect size (d = 0.09) suggest incomplete evening heat dissipation but insufficient contrast to generate meaningful atmospheric change. This pattern points to sustained radiative heat retention within the built environment.

Relative humidity showed a significant reduction from 85.69% in the morning to 84.74% in the evening (*p = 0.016*), with a moderate effect size (d = 0.52). This trend indicates a transition to a drier evening air mass, commonly associated with daytime convective mixing and evolving temperature gradients. Reduced evening humidity may enhance particulate resuspension and influence thermal comfort conditions.

Table 6: Statistical Analysis of Climatic Variables (Shapiro–Wilk, Paired *t*-test, Wilcoxon, and Cohen's *d*) – Ubeji Community

Parameter	Session	Mean ± SEM	Shapiro–Wilk (p)	Test Used	t / W Statistic	p-Value	Cohen's *d*	Interpretation
Noise (dB)	Morning	55.12 ± 1.08	0.152	Paired *t*-test	*t* (39) =2.43	0.020*	0.56	Evening noise significantly higher; moderate effect
	Evening	56.59 ± 0.64	0.124					
Temperature (°C)	Morning	32.56 ± 0.29	0.243	Paired *t*-test	*t* (39) =0.38	0.707	0.09	No significant difference; very small effect
	Evening	32.65 ± 0.27	0.189					
Humidity (%)	Morning	85.69 ± 1.36	0.081	Wilcoxon	*W*=118	0.016*	0.52	Significant decline in humidity; moderate effect
	Evening	84.74 ± 1.50	0.048					

(*Significant difference at p < 0.05*)

The comparative analysis of climatic variables between Ekpan and Ubeji revealed significant diurnal variations in noise level, temperature, and humidity, reflecting both anthropogenic influences and coastal atmospheric dynamics characteristic of the Niger Delta. These findings align with recent studies indicating that industrialised settlements within the Warri–Effurun axis experience altered microclimates due to combined emissions, surface modifications, and high population densities (Okoro *et al*., 2022; Ede *et al*., 2023) [13, 28].

Mean daytime temperatures across both communities (ranging from 32–33 °C) corroborate patterns typical of humid equatorial regions, where persistent convective activity, high moisture content, and weak wind circulation limit heat dispersion (Ojekunle *et al*., 2020) [24]. The absence of a significant difference between morning and evening temperatures in both Ekpan and Ubeji supports the assertion that urban areas exhibit reduced diurnal thermal amplitude—a phenomenon widely attributed to the urban heat island (UHI) effect (Adebayo *et al*., 2021) [3]. Elevated land surface temperatures have been consistently reported in Warri, Port Harcourt, and Lagos industrial corridors, where built-up surfaces and petroleum-processing activities trap radiant heat and prolong nocturnal warming (Etim & Enete, 2023; Akpoborie & Esegbue, 2021) [8, 16].

Humidity levels exhibited a clear downward shift from morning to evening in both sites, a trend indicative of progressive solar heating and vapour dilution with atmospheric mixing. Similar humidity fluctuations have been observed in coastal refinery towns where afternoon insolation drives strong evapotranspiration followed by evening desiccation (Otaru *et al*., 2022) [33]. The persistently high morning humidity (>85 %) at both Ekpan and Ubeji suggests strong maritime influence, consistent with the Niger Delta's proximity to the Atlantic Ocean and the presence of wetlands and mangroves (Okolie *et al*., 2021) [27].

The observed increase in evening noise intensity across both communities (Ekpan: 54.87 → 56.42 dB; Ubeji: 55.12 → 56.59 dB) demonstrates the growing dominance of anthropogenic acoustic pollution, especially during post-work and market closure hours. Similar diurnal peaks in environmental sound levels have been documented in oil-producing urban settlements due to dense traffic, industrial shifts, and community energy generator usage (Olanrewaju *et al*., 2020; Chukwu *et al*., 2021) [12, 29].

According to WHO guidelines (2022), permissible community noise exposure should not exceed 55 dB during daytime; however, both locations consistently approached or slightly exceeded this threshold. Chronic exposure to such levels has been associated with physiological stress and reduced cognitive performance among residents (Adedeji *et al*., 2023) [4]. The statistical confirmation of moderate effect sizes (Cohen's d ≈ 0.5) in both cases underscores the tangible environmental and health implications of urban acoustic accumulation.

The correlation between noise elevation and reduced humidity observed in the evening sessions may indicate synergistic atmospheric stress. As air dries and temperature stabilises, sound propagation becomes more efficient due to lower absorption by water vapour molecules (Onuorah & Okechukwu, 2022) [31]. Consequently, noise attenuation decreases, producing perceptibly louder ambient environments. The interplay between meteorological and acoustic parameters in industrial neighbourhoods such as Ubeji and Ekpan thus exemplifies the broader urban–industrial coupling phenomenon described in contemporary environmental climatology (Okafor *et al*., 2024) [25].

Spatially, Ekpan recorded slightly higher humidity means than Ubeji, despite both being part of the same hydroclimatic belt. This distinction may result from the denser industrial infrastructure in Ekpan, which contributes to increased particulate concentration and water vapour retention through combustion emissions and effluent discharge (Efe *et al*., 2020) [14]. Conversely, Ubeji's proximity to open coastal airsheds may promote stronger advection and vertical mixing, leading to faster evening desiccation and slightly lower relative humidity (Akinbode *et al*., 2021) [7].

Temperature stability and moderate humidity across both sites align with the tropical rainforest microclimate typology, where latent heat fluxes dominate over sensible heat. Similar findings have been reported by Ojeifo *et al*. (2023) [23], who observed comparable microclimatic homogeneity among settlements along the Warri–Ughelli corridor. Moreover, the interplay of anthropogenic heat, vehicular emissions, and industrial flaring at low atmospheric levels contributes to the formation of shallow nocturnal inversion layers, suppressing convective cooling (Ebeku & Olaniran, 2022).

The concurrent rise in sound intensity and decline in humidity have practical implications for public health and urban design. Elevated ambient temperatures and drier evening air enhance pollutant dispersion, but they also increase the risk of respiratory irritation and dehydration, especially in vulnerable populations (Nwankwo *et al*., 2021) [21]. In both communities, persistent exposure to mild acoustic and thermal stressors could lead to cumulative physiological burdens, including elevated cortisol levels and sleep disruption (Agbede *et al*., 2023) [6].

Climate adaptation strategies in these refinery-proximal settlements should prioritise greenbelt establishment, regulation of industrial acoustic output, and implementation of community-based air-quality and meteorological monitoring. Vegetation buffers have been proven to simultaneously reduce urban heat and absorb acoustic energy, thus restoring microclimatic balance (Ologunorisa *et al*., 2024) [30]. Furthermore, structured zoning policies separating residential clusters from high-noise or high-emission facilities are essential to mitigate the combined climatic and anthropogenic stress identified in this study.

The climatic trends in Ekpan and Ubeji exemplify urban coastal atmospheric coupling, where industrialisation modifies local climate without fully overriding natural maritime influences. The relative uniformity in temperature yet divergence in humidity and noise signatures reflect dynamic equilibrium between anthropogenic heat fluxes and oceanic moderation. This duality mirrors patterns described in other coastal petro-industrial cities such as Bonny, Port Harcourt, and Escravos (Okeke *et al*., 2023; Etemike *et al*., 2022) [15, 26].

By integrating continuous monitoring and statistical modelling, this analysis highlights how temporal climatic asymmetries (morning vs evening) can serve as early indicators of environmental stress. The moderate effect magnitudes, though not extreme, suggest gradual but cumulative alteration of the atmospheric baseline—an early warning of urban climatic transition. Sustained research across seasonal cycles is therefore imperative for establishing adaptive frameworks aligned with Sustainable Development Goal 13 on climate action and Goal 11 on sustainable cities.

Conclusion

From the findings, it is concluded that both Ekpan and Ubeji communities experience measurable diurnal fluctuations in environmental parameters shaped by the combined effects of industrial activity, vehicular movement, and prevailing meteorological conditions. Evening periods were characterised by elevated noise levels that exceeded the World Health Organization's 55 dB threshold, indicating a potential risk of chronic acoustic exposure for residents. Relative humidity declined towards dusk, reflecting increased atmospheric dryness driven by industrial heat release and convective mixing processes. In contrast, temperature remained persistently high across both morning and evening sessions, suggesting strong urban heat retention and limited nocturnal cooling consistent with urban heat island effects. Although measured gaseous pollutants remained within permissible limits, the observed evening elevations in CO_2 and total volatile organic compounds indicate progressive air quality stress associated with industrial emissions and fossil fuel combustion. Spatially, both Ekpan and Ubeji exhibited comparable climatic and atmospheric signatures despite differences in industrial intensity, confirming the influence of a shared coastal microclimatic regime governed by the Niger Delta's maritime air mass. Overall, the environmental profiles of both communities depict a transitioning urban coastal ecosystem in which sustained anthropogenic pressures interact with natural humidity and temperature regulation cycles, leading to gradual accumulation of atmospheric stress.

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