Multi-Pollutant Concentrations and Environmental Management Implications in Data-Scarce Kula Kingdom Coastal Communities, Rivers State, Nigeria

[*1]Christian Livingstone Otiasah, [2]Adonis Perron Sampson, [3]Noble, Chianigam Brown

[1]Lecturer in the Department of Environmental Management, Ignatius Ajuru University of Education, Rumuelumeni, Port Harcourt; Nigeria. His research interests include water supply and sanitation, environmental Hydrology, Marine Ecological Health, Marine Resource Pollution and Waste Management.

[2]Lecturer in the Department of Environmental Management, Ignatius Ajuru University of Education, Rumuelumeni, Port Harcourt. His research interest is in climatology and atmospheric chemistry and environmental management

[3]Lecturer in the Department of Geography and Environmental Management, Ignatius Ajuru University of Education, Rumuelumeni, Port Harcourt; Nigeria. His research interest is in Disaster Risk Management, Spatial Analysis on Flooding, Gas Flaring, NDVI, Hydrological Modelling (Watershed Analysis) & Environmental Management

***Corresponding Author**

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ABSTRACT

Coastal communities situated within hydrocarbon-producing regions of the Niger Delta face persistent air quality pressures that remain largely undocumented at the community scale. This study assessed multi-pollutant ambient air quality across five sampling locations in the Kula Kingdom coastal communities of Rivers State, Nigeria, namely Robert Kiri, Offoin-Ama, Belema, Kula Water Front and Atlantic Ocean Shore. Concentrations of particulate matter (PM2.5 and PM10), methane, volatile organic compounds, nitrogen dioxide, sulphur dioxide and ozone were measured using portable air quality monitoring equipment and benchmarked against the World Health Organization air quality guidelines, the United States Environmental Protection Agency National Ambient Air Quality Standards, and Nigeria's National Environmental Standards and Regulations Enforcement Agency and Federal Ministry of Environment thresholds. PM10 concentrations ranged from 0.033 to 0.245 mg/m3, with Belema recording the highest average value, while PM2.5 ranged from 0.017 to 0.042 mg/m3. Volatile organic compound concentrations were markedly elevated at Offoin-Ama and Robert Kiri, exceeding 84,000 ppb on average. Nitrogen dioxide rose progressively across the sampling transect, peaking at Kula Water Front (0.553 ppm), while sulphur dioxide and ozone remained largely negligible except at isolated locations. Air Quality Index values calculated from particulate matter concentrations classified Belema as Unhealthy for Sensitive Groups, while the remaining locations fell within the Moderate category. Correlation analysis revealed a strong positive association between methane and volatile organic compounds and a strong inverse association between nitrogen dioxide and both methane and volatile organic compounds, patterns broadly consistent with mixed contributions from gas flaring, flow station operations and combustion-related sources reported elsewhere in the Niger Delta. The tri-standard comparison exposed substantial divergence in how exceedance is judged depending on which regulatory framework is applied, with implications for how environmental management decisions are made in data-scarce settings of this kind. The findings support the case for sustained, community-level air quality monitoring and more specific emission control measures in hydrocarbon-adjacent coastal settlements.

Keywords: ambient air quality; particulate matter; volatile organic compounds; Niger Delta; gas flaring; Air Quality Index; environmental management; coastal communities

INTRODUCTION

Ambient air pollution remains one of the more persistent environmental health burdens of the present century, particularly in regions where industrial activity and dense settlement overlap. Exposure to elevated concentrations of airborne pollutants has been linked to respiratory and cardiovascular disease, reduced life expectancy and broader disruption of ecosystem processes, and the scale of this burden has pushed air quality monitoring to the centre of environmental policy discussions in many parts of the world (Manisalidis et al., 2020). Across sub-Saharan Africa, the sources driving this pollution differ in emphasis from those typically studied in higher-income settings. Vehicular traffic, industrial discharge, wildfire smoke and household biomass combustion together shape ambient conditions on the continent, and indoor pollutant concentrations in many African homes already exceed the levels recommended by international guidelines (Agbo et al., 2020). Nigeria's own air quality challenges follow a broadly similar pattern, though petroleum extraction, refining and gas flaring introduce an additional and fairly distinct pollutant signature into communities that host these activities.

A national review of Nigerian air quality separates natural sources, such as windborne dust and wildfire smoke, from anthropogenic sources including vehicular emissions, mining and industrial discharge, and concludes that monitoring infrastructure across the country's urban centres remains too sparse to track either category with confidence (Abaje et al., 2020). The drivers behind this pattern are not confined to transport and manufacturing. A review focused specifically on the origins of anthropogenic emissions within Nigeria identifies gas flaring, petroleum refining and land-use change, including deforestation and agricultural burning, as recurring and largely unregulated contributors to the national emissions profile, and argues that cleaner energy policy is the most direct lever available for reducing them (Okedere et al., 2021). That argument sits somewhat apart from the more localised interventions proposed elsewhere in the Niger Delta literature, and the distance between national policy recommendations and conditions in specific host communities is a gap this study returns to in later sections.

Within the Niger Delta specifically, the environmental burden of hydrocarbon extraction has been framed by some authors as a question of environmental injustice: the region generates the bulk of Nigeria's oil revenue yet carries a disproportionate share of the resulting pollution, with gas flaring, fossil fuel combustion and artisanal crude refining identified as the dominant local sources of degraded air quality (Echendu et al., 2022). This framing is useful because it shifts the analytical question away from simply cataloguing pollutant concentrations and toward asking who is exposed, and why monitoring in these host communities has historically lagged behind monitoring elsewhere in the country. A recent assessment across six local government areas of Rivers State illustrates both the scale of the problem and the seasonal pattern that appears to govern it, with concentrations of sulphur dioxide, nitrogen dioxide, particulate matter, hydrogen sulphide and volatile organic compounds all rising during the dry season and several pollutants exceeding NESREA's regulatory limits by a considerable margin (Ogbuagu et al., 2025). Similar exceedances have been reported in industrial hubs such as Port Harcourt, Eleme, Bonny and Omoku, where particulate matter levels measured well above World Health Organization limits (Chinda et al., 2026).

Coastal and estuarine communities within the Niger Delta occupy a particular position in this literature. Studies conducted in Bonny, Bille and Degema found that oil-related activity, including flaring, measurably degraded air quality relative to World Health Organization guidance, with nitrogen dioxide levels varying significantly between the three towns depending on their proximity to flow stations and vehicular traffic (Jumbo et al., 2023). Comparable findings were reported around Bonny Island, where sulphur dioxide remained within permissible limits but ground-level ozone, hydrogen sulphide, nitrogen dioxide and particulate matter exceeded World Health Organization thresholds at nearly every sampling point (Ogolo et al., 2025). Crude oil producing communities in neighbouring Bayelsa State showed a similarly sharp seasonal contrast, with dry season particulate matter concentrations several times higher than wet season values and gas flaring identified as a dominant contributing source (Ezekwe et al., 2026). What these studies share is not only elevated pollutant concentrations but a common absence of sustained, community-specific monitoring: most of the underlying data comes from short field campaigns rather than continuous observation, a limitation that mirrors the situation in Kula Kingdom.

Kula Kingdom, situated along the tidally influenced Atlantic coastline of Rivers State, sits within this broader hydrocarbon-producing corridor but has received comparatively little direct air quality attention in the published literature. Its coastal communities combine residential settlement with proximity to oil and gas infrastructure, tidal creek systems and, in places, artisanal refining activity of the kind documented elsewhere in the Niger Delta as a source of carbon monoxide and hydrocarbon emissions (Ki & Abbey, 2022). The absence of baseline air quality data for these communities is not simply an academic gap. Without location-specific measurements, neither regulators nor residents have a defensible basis for judging whether ambient conditions in Kula Kingdom resemble those reported in Bonny, Ogbia or the industrial hubs further inland, and any environmental management response risks being generic rather than targeted to the pollutant mix and exposure pathways actually present in the area.

1.2 Aim and Objectives

This study aims to assess multi-pollutant ambient air quality and derive environmental management implications for the data-scarce, hydrocarbon-influenced coastal communities of Kula Kingdom, Rivers State. Two specific objectives guide the study:

1. To determine the spatial concentrations of key air pollutants (PM2.5, PM10, CH4, VOCs, NO2, SO2 and O3) across five selected Kula Kingdom coastal communities and evaluate these concentrations against the World Health Organization, United States Environmental Protection Agency, and Nigeria's National Environmental Standards and Regulations Enforcement Agency and Federal Ministry of Environment air quality standards.

2. To assess pollutant source associations, through correlation analysis and Air Quality Index classification, and to derive environmental management implications for hydrocarbon-impacted, data-scarce coastal settings of this kind.

1.3 Study Area

Kula Kingdom lies within Akuku-Toru Local Government Area of Rivers State, on the Atlantic-facing coastline of the eastern Niger Delta. The area is characterised by a network of tidal creeks and estuarine waterways that connect its constituent communities to the open ocean, and settlement patterns follow this hydrology closely, with homes, fishing activity and, in parts of the wider region, oil and gas infrastructure situated close to the waterline. Five locations were selected for air quality sampling along a transect running from the more inland, creek-adjacent settlements toward the open Atlantic shoreline: Robert Kiri, Offoin-Ama, Belema, Kula Water Front and Atlantic Ocean Shore. This arrangement allowed the study to capture any gradient in pollutant concentration associated with proximity to hydrocarbon infrastructure, tidal influence, or distance from the open ocean, rather than treating the kingdom as a single undifferentiated sampling point. Figure 1 presents a map of the study area showing the five sampling locations.

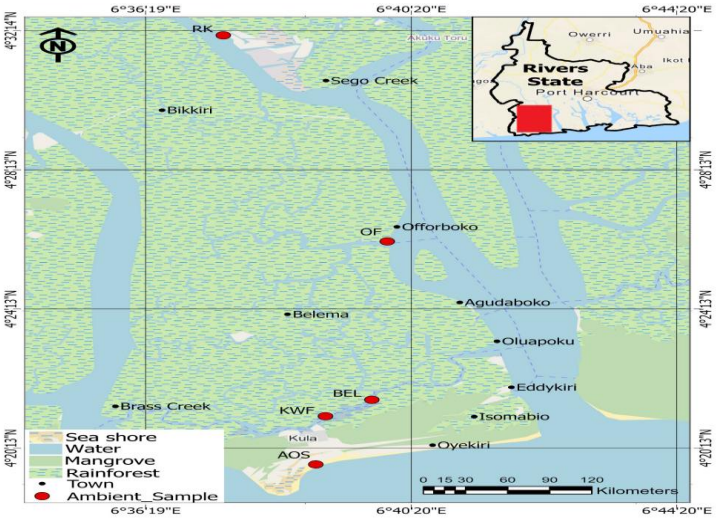


Figure1 Map of the Study Area Showing the Five Sampling Locations Across Kula Kingdom Coastal Communities, Rivers State

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MATERIALS AND METHODS

2.1 Study Design and Sampling Locations

A cross-sectional field monitoring design was adopted, with ambient air quality parameters measured at five fixed sampling locations across Kula Kingdom during a single monitoring campaign in 2026. Sampling proceeded sequentially along the inland-to-coastal transect described in Section 1.5, beginning at Robert Kiri and ending at Atlantic Ocean Shore, with each location monitored for a defined period under broadly comparable atmospheric conditions to limit meteorological variability between sites. Table 1 summarises the sampling locations, their recorded positions, and the time window during which measurements were taken at each site.

Table 1 Sampling Locations, GPS Coordinates and Sampling Time

Location	Code	GPS Position (as recorded)	Sampling Time
Robert Kiri	RK	40°534'78" N, 60°624'94" E	1:30 pm - 1:55 pm
Offoin-Ama	OF	40°436'02" N, 60°661'38" E	2:30 pm - 2:53 pm
Belema Community	BEL	40°360'06" N, 60°6622'5" E	3:29 pm - 3:52 pm
Kula Water Front	KWF	40°352'19" N, 60°650'61" E	4:03 pm - 4:26 pm
Atlantic Ocean Shore	AOS	40°329'08" N, 60°648'19" E	5:06 pm - 5:32 pm

Note. Field survey, 2026.

2.2 Instrumentation and Calibration

Ambient concentrations of particulate matter, methane, volatile organic compounds, nitrogen dioxide, sulphur dioxide and ozone were measured using a portable multi-parameter air quality monitoring instrument, consistent with the handheld and portable monitoring approaches widely used in comparable Niger Delta field studies (Ehumadu et al., 2021; Akhionbare et al., 2020). The instrument was calibrated according to the manufacturer's standard procedure prior to fieldwork, and measurements at each location were taken under stable outdoor conditions to reduce the influence of short-term wind gusts or localised disturbance on individual readings.

2.3 Parameters Monitored

Seven atmospheric parameters were monitored at each location: fine particulate matter (PM2.5), coarse particulate matter (PM10), methane (CH4), total volatile organic compounds (VOC), nitrogen dioxide (NO2), sulphur dioxide (SO2) and ground-level ozone (O3). This pollutant combination reflects the mix most consistently reported in Niger Delta air quality assessments associated with hydrocarbon extraction, gas flaring and combustion-related activity (Ogbuagu et al., 2025; Yorkor et al., 2021), and allows the present findings to be compared directly against that body of work.

2.4 Data Analysis

Descriptive statistics, minimum, maximum and mean concentrations, were computed for each pollutant at each location. An Air Quality Index was calculated for particulate matter using the United States Environmental Protection Agency's standard breakpoint method, which converts a measured pollutant concentration into an index value on a common 0-500 scale and assigns it to one of six descriptive categories ranging from Good to Hazardous, an approach whose historical development and continued relevance for communicating air quality risk to non-specialist audiences has been documented extensively (Horn & Dasgupta, 2023). Pearson correlation coefficients were computed across the seven monitored pollutants using the location-level mean concentrations, to examine whether pollutants known to share common combustion or flaring-related origins in the Niger Delta

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literature displayed statistically coherent relationships in the Kula Kingdom dataset. Given that the analysis is based on five sampling locations, the correlation results are treated as indicative of association rather than as a basis for strong causal inference.

2.5 Regulatory Benchmarks

Observed pollutant concentrations were compared against three regulatory frameworks: the World Health Organization's 2021 global air quality guidelines, the United States Environmental Protection Agency's National Ambient Air Quality Standards, and Nigeria's own regulatory limits as set out by the National Environmental Standards and Regulations Enforcement Agency and the Federal Ministry of Environment. A tri-standard comparison was adopted because Nigerian regulatory limits for several pollutants remain considerably less stringent than either the WHO or USEPA benchmarks, a divergence noted directly in Nigerian air quality studies that have applied more than one standard side by side (Daful et al., 2020). Relying on a single standard risks understating or overstating the severity of observed conditions depending on which threshold happens to be closest to local practice; comparing all three offers a more complete picture of where Kula Kingdom's air quality sits relative to both international guidance and domestic regulation. Table 2 summarises the threshold values applied for each pollutant under each framework.

Table 2 WHO, USEPA and NESREA/FMEnv Threshold Values for Monitored Pollutants

Pollutant	**Averaging Period**	**WHO (2021) Guideline**	**USEPA NAAQS**	**NESREA / FMEnv (Nigeria)**
PM2.5	24-hour	15 µg/m³	35 µg/m³	250 µg/m³ (historic FMEnv limit)
PM10	24-hour	45 µg/m³	150 µg/m³	250 µg/m³ (historic FMEnv limit)
NO2	1-hour	200 µg/m³ (~0.106 ppm)	100 ppb (0.100 ppm)	0.04-0.06 ppm (varies by source)
SO2	24-hour	40 µg/m³ (~0.015 ppm)	75 ppb (1-hour)	0.01-0.1 ppm (varies by source)
O3	8-hour	100 µg/m³ (~0.05 ppm)	0.070 ppm	Not separately codified
CH4	Not health-based	No WHO guideline (climate pollutant)	No NAAQS (non-criteria pollutant)	Not separately codified
VOC (total)	Not standardised	No single WHO guideline	No single NAAQS	Not separately codified

Note. World Health Organization (2021) global air quality guidelines; United States Environmental Protection Agency National Ambient Air Quality Standards; Nigeria NESREA/FMEnv regulatory limits as applied in Daful et al. (2020).

RESULTS

3.1 Pollutant Concentrations by Location

Table 3 presents the minimum, maximum and average concentrations recorded for all seven monitored pollutants across the five sampling locations. The dataset shows considerable variation both across locations and, for particulate matter in particular, within individual sampling periods.

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Table3 Summary of Minimum, Maximum and Average Pollutant Concentrations Across Sampling Locations

Location	Pollutant	Minimum	Maximum	Average
Robert Kiri	PM2.5	0.026	0.030	0.028
	PM10	0.058	0.125	0.086
	CH4	261	283	270
	O3	0.000	0.000	0.000
	SO2	0.000	0.000	0.000
	VOC	78628	97521	84710
	NO2	0.250	0.250	0.250
Offoin-Ama	PM2.5	0.017	0.021	0.018
	PM10	0.031	0.036	0.033
	CH4	204	210	208
	O3	0.001	0.001	0.001
	SO2	0.100	0.100	0.100
	VOC	88753	97521	90043
	NO2	0.337	0.337	0.337
Belema	PM2.5	0.018	0.067	0.042
	PM10	0.031	0.696	0.245
	CH4	139	147	144
	O3	0.000	0.000	0.000
	SO2	0.000	0.000	0.000
	VOC	38845	40476	39032
	NO2	0.432	0.432	0.432
Kula Water Front	PM2.5	0.017	0.018	0.017
	PM10	0.033	0.038	0.035
	CH4	111	112	111
	O3	0.000	0.000	0.000
	SO2	0.000	0.000	0.000
	VOC	28257	29057	28418
	NO2	0.553	0.553	0.553

Atlantic Ocean Shore	PM2.5	0.018	0.036	0.024
	PM10	0.054	0.125	0.088
	CH4	68	71	70
	O3	0.015	0.015	0.015
	SO2	0.000	0.000	0.000
	VOC	23540	24214	23381
	NO2	0.497	0.497	0.497

Note. Field survey, 2026.

3.2 Spatial Variation of Particulate Matter

PM10 concentrations varied nearly eightfold across the five locations, from an average of 0.033 mg/m3 at Offoin-Ama to 0.245 mg/m3 at Belema, where the recorded maximum reading of 0.696 mg/m3 was the single highest particulate measurement obtained anywhere in the study. PM2.5 followed a broadly similar pattern, with Belema again recording the highest average concentration at 0.042 mg/m3 against a low of 0.017 mg/m3 at Kula Water Front. The remaining three locations, Robert Kiri, Offoin-Ama and Atlantic Ocean Shore, clustered at intermediate particulate levels rather than tracking the extremes at either end of the transect.

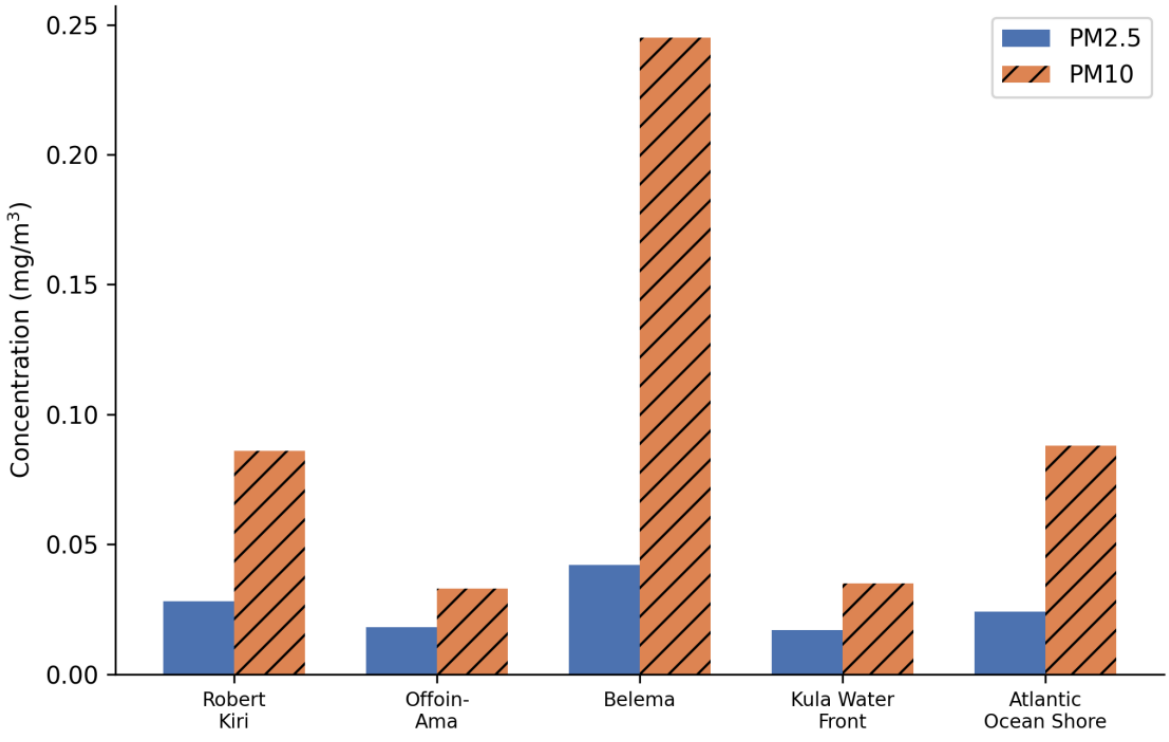


Figure 2 Average PM2.5 and PM10 Concentrations Across Sampling Locations

3.3 Volatile Organic Compounds

Volatile organic compound concentrations were the most striking feature of the dataset, with values recorded in the tens of thousands of parts per billion at every location. Offoin-Ama and Robert Kiri returned the highest averages, at 90,043 ppb and 84,710 ppb respectively, while Atlantic Ocean Shore recorded the lowest average

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at 23,381 ppb. This roughly fourfold decline in VOC concentration moving from the inland end of the transect toward the open Atlantic shoreline is one of the clearer spatial gradients in the dataset.

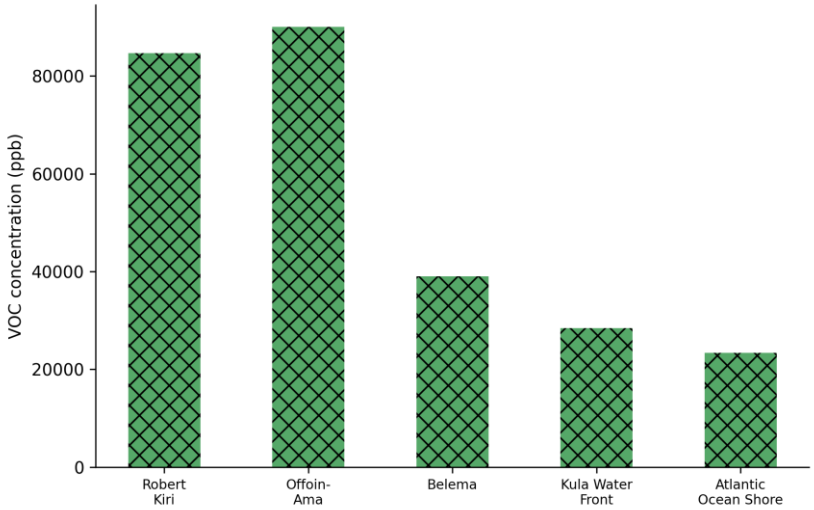


Figure 3 Average VOC Concentrations Across Sampling Locations

3.4 Nitrogen Dioxide

Nitrogen dioxide displayed a pattern almost inverse to that of VOCs, rising steadily from 0.250 ppm at Robert Kiri to a peak of 0.553 ppm at Kula Water Front before declining slightly to 0.497 ppm at Atlantic Ocean Shore. Belema and Offoin-Ama fell between these extremes at 0.432 ppm and 0.337 ppm respectively. Unlike the particulate matter and VOC data, where minimum and maximum values sometimes diverged substantially within a single location, NO2 readings were uniform within each site, suggesting comparatively stable conditions during the short sampling window at each location.

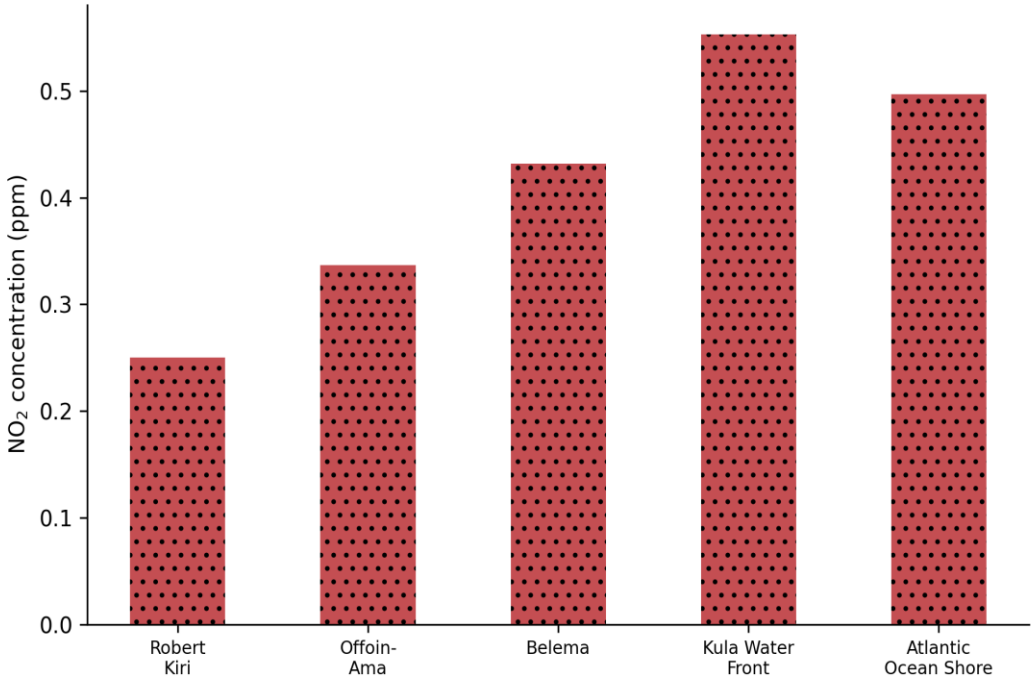


Figure4 Average NO2 Concentrations Across Sampling Locations

3.5 Sulphur Dioxide and Ozone

SO2 and O3 were, by comparison, minor features of the dataset. SO2 was detected only at Offoin-Ama, at a constant 0.100 ppm, and returned a reading of zero at all four remaining locations. Ozone showed a similarly

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narrow distribution, registering 0.015 ppm at Atlantic Ocean Shore and 0.001 ppm at Offoin-Ama, with all other locations recording no detectable ozone. The near-absence of both pollutants across most of the transect stands in contrast to the elevated readings for particulate matter, VOCs and NO2, and is addressed further in the Discussion.

3.6 Tri-Standard Exceedance Comparison

Comparing observed PM2.5 and PM10 averages against the WHO, USEPA and NESREA/FMEnv thresholds in Table 2 produces markedly different exceedance patterns depending on which standard is applied. Every location exceeded the WHO 24-hour PM2.5 guideline of 15 µg/m3, including Kula Water Front, which recorded the lowest PM2.5 average in the dataset. Against the considerably less stringent USEPA 24-hour standard of 35 µg/m3, however, only Belema exceeded the threshold, with the remaining four locations falling within the permitted range. A similar divergence appears for PM10: four of the five locations exceeded the WHO guideline of 45 µg/m3, while only Belema, at 245 µg/m3, approached the USEPA limit of 150 µg/m3. None of the five locations breached the older, comparatively permissive NESREA/FMEnv historic limit of 250 µg/m3 for either pollutant, and only Belema came close to doing so.

Table 4 Observed PM2.5 and PM10 Concentrations Against WHO and USEPA Thresholds

Location	**PM2.5 (µg/m³)**	**WHO**	**USEPA**	**PM10 (µg/m³)**	**WHO**	**USEPA**
Robert Kiri	28.0	Exceeds	Within limit	86.0	Exceeds	Within limit
Offoin-Ama	18.0	Exceeds	Within limit	33.0	Within limit	Within limit
Belema	42.0	Exceeds	Exceeds	245.0	Exceeds	Exceeds
Kula Water Front	17.0	Exceeds	Within limit	35.0	Within limit	Within limit
Atlantic Ocean Shore	24.0	Exceeds	Within limit	88.0	Exceeds	Within limit

Note. Author's analysis of field survey data, 2026, against thresholds in Table 2.

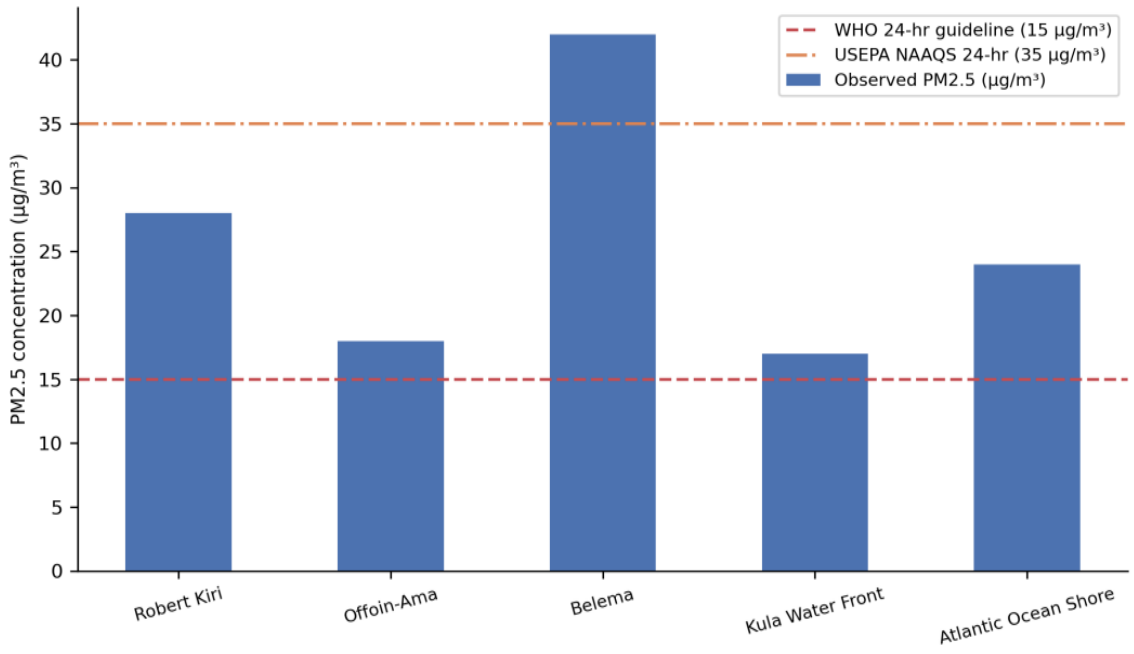


Figure5 Observed PM2.5 Concentrations Against WHO and USEPA 24-Hour Benchmarks

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3.7 Air Quality Index Classification

Air Quality Index values calculated from the particulate matter data classify four of the five locations as Moderate, with index values ranging from 61 at Kula Water Front to 84 at Robert Kiri. Belema stands apart, returning an overall AQI of 146 driven by its PM10 reading, placing it in the Unhealthy for Sensitive Groups category. This is the only location in the dataset where the calculated AQI crosses into a category associated with direct health guidance for at-risk groups such as children, older adults and individuals with existing respiratory conditions.

Table 5
Estimated Air Quality Index Values and Classification by Location

Location	PM2.5 AQI	PM10 AQI	Overall AQI	Category
Robert Kiri	84	66	84	Moderate
Offoin-Ama	63	31	63	Moderate
Belema	117	146	146	Unhealthy for Sensitive Groups
Kula Water Front	61	32	61	Moderate
Atlantic Ocean Shore	76	67	76	Moderate

Note. Author's calculation using USEPA AQI breakpoint methodology applied to field survey data, 2026.

3.8 Correlation Analysis

Table 6 presents Pearson correlation coefficients computed across the seven monitored pollutants using location-level mean concentrations. The strongest association in the dataset is between PM2.5 and PM10 (r = 0.980), which is expected given that PM2.5 is a subset of the PM10 size fraction. Methane and VOC concentrations are also strongly and positively correlated (r = 0.927), while both pollutants show a strong negative correlation with NO2 (r = -0.939 for CH4, r = -0.914 for VOC). SO2 shows a moderate positive association with VOC (r = 0.648) but a moderate negative association with both particulate fractions. Because these coefficients are derived from only five location-level observations, they should be read as descriptive of pattern rather than as statistically confirmed relationships, and this limitation is addressed further in the Discussion.

Table6 Pearson Correlation Matrix Among Monitored Pollutants (Location-Level Means, n = 5)

	PM2.5	PM10	CH4	O3	SO2	VOC	NO2
PM2.5	1.000	0.980	0.063	-0.130	-0.431	-0.137	-0.171
PM10	0.980	1.000	-0.102	-0.090	-0.415	-0.271	0.001
CH4	0.063	-0.102	1.000	-0.625	0.334	0.927	-0.939
O3	-0.130	-0.090	-0.625	1.000	-0.186	-0.486	0.364
SO2	-0.431	-0.415	0.334	-0.186	1.000	0.648	-0.352
VOC	-0.137	-0.271	0.927	-0.486	0.648	1.000	-0.914
NO2	-0.171	0.001	-0.939	0.364	-0.352	-0.914	1.000

Note. Author's analysis of field survey data, 2026.

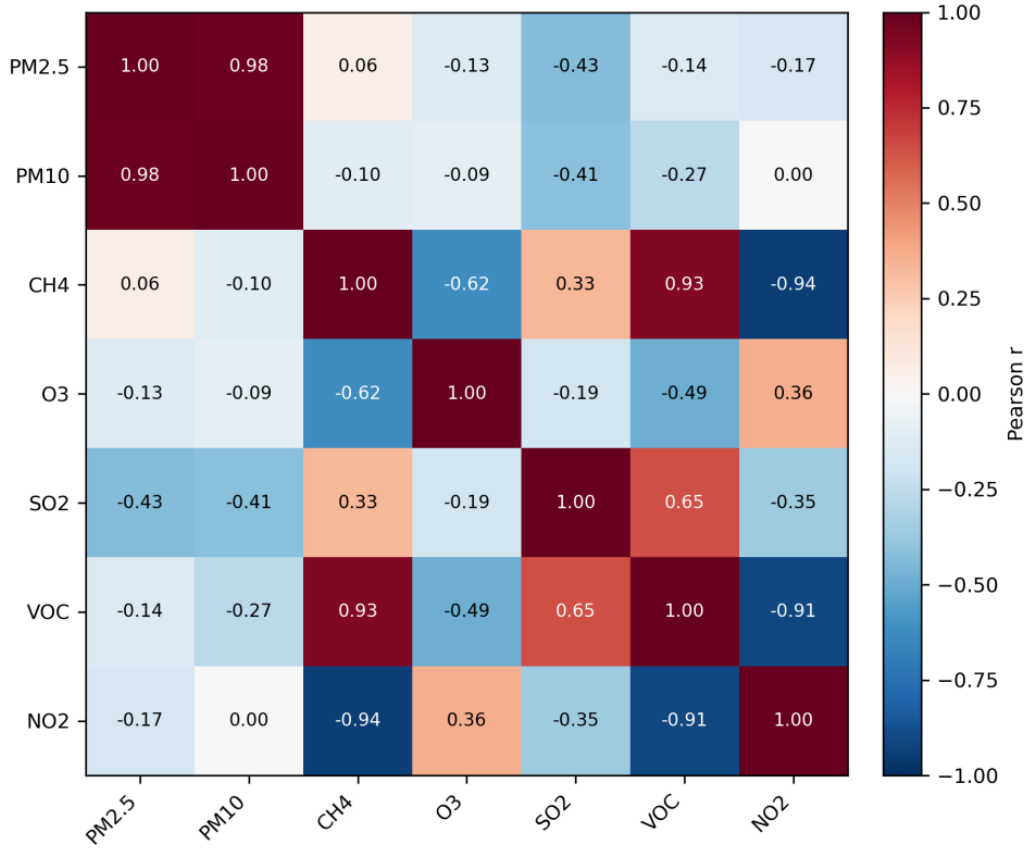


Figure 6 Pearson Correlation Matrix Among Monitored Pollutants

DISCUSSION

4.1 Spatial Patterns and Hydrocarbon and Tidal Influence

The particulate matter peak recorded at Belema is difficult to attribute to a single cause on the basis of the present data alone, but its scale, nearly eight times the PM10 average at the cleanest location, mirrors the kind of localised spike reported around flow stations and gas flare sites elsewhere in the Niger Delta, where particulate concentrations decline sharply with distance from the flare stack (Ehumadu et al., 2021; Nwosisi et al., 2021). If a comparable point source exists within or near Belema, whether a flow station, generator use, or another combustion activity concentrated at that location, it would explain why the particulate anomaly is confined to a single site rather than appearing as a smoother gradient across the transect. The VOC pattern tells a different spatial story. Concentrations were highest at the more inland locations, Robert Kiri and Offoin-Ama, and declined toward the open Atlantic shoreline, a gradient consistent with dilution and dispersion of VOC-bearing emissions as distance from likely inland sources, whether flaring, artisanal refining, or vessel traffic on the creek system, increases. Tidal exchange along this stretch of coastline may also contribute to this pattern, since incoming and outgoing tidal flows can influence local air movement and pollutant dispersion in ways that a single-day sampling campaign cannot fully resolve.

4.2 Cross-Standard Divergence and Regulatory Implications

The exceedance comparison in Section 3.6 illustrates a problem that is as much regulatory as it is atmospheric. Every sampling location in Kula Kingdom exceeded the WHO PM2.5 guideline, yet only one location exceeded the corresponding USEPA standard, and none breached the older NESREA/FMEnv limit. A community assessed purely against Nigeria's domestic threshold would appear to have acceptable air quality at four of five locations; the same community assessed against WHO guidance would appear to have a pollution problem everywhere. This is not a contradiction in the data so much as a reflection of how far Nigerian regulatory limits for particulate matter still sit from international guidance, a divergence documented directly in comparative Nigerian AQI

studies that have applied more than one standard to the same dataset (Daful et al., 2020). The practical consequence is that the choice of benchmark is not a neutral technical decision. It determines whether Kula Kingdom's air quality is officially treated as a problem requiring intervention or as broadly within acceptable limits, and any environmental management response built on a single national threshold risks understating the exposure that residents are, according to WHO-based criteria, actually experiencing.

4.3 Probable Emission Sources

The correlation pattern reported in Section 3.8 offers some indication of shared or competing sources, though the small number of sampling locations limits how far this can be pushed. The strong positive association between methane and VOCs is consistent with both pollutants originating from the same combustion or venting processes, a relationship documented in gas flaring emission studies across the Niger Delta, where flared gas releases substantial volumes of methane alongside a mixture of volatile organic compounds (Ukhurebor et al., 2024; Okpoji et al., 2025). The strong negative association between these two pollutants and NO2, by contrast, is less straightforward to interpret from the present dataset alone. One plausible reading is that NO2 in Kula Kingdom is driven more by vehicular and generator combustion at specific locations, such as Kula Water Front, than by the flaring-associated processes that appear to dominate the methane and VOC signal further inland, a divergence in source type that would be consistent with the general pattern described in reviews of gas flaring's lifecycle and localisation within Niger Delta oil and gas facilities (Emekwuru, 2024). SO2's isolated detection at Offoin-Ama, and its moderate positive correlation with VOC, is also consistent with a discrete, localised combustion source at that site rather than a region-wide sulphur signal, echoing the highly localised SO2 detections reported around individual flare sites and artisanal refining operations elsewhere in the delta (Onakpohor et al., 2020).

4.4 Significance for Closing the Data-Scarcity Gap

Whatever the precise source attribution, the Kula Kingdom dataset adds a location-specific record to a Niger Delta air quality literature that remains, on the whole, concentrated around a relatively small number of well-studied industrial hubs, Port Harcourt, Eleme, Bonny and a handful of named flow stations chief among them. Communities positioned along smaller tidal creek systems, without an obvious single point-source such as a named flow station, have tended to fall outside this monitoring effort, not because their air quality is assumed to be better, but because no comparable data exists to say otherwise one way or another. The present findings suggest that Kula Kingdom's air quality, at least with respect to particulate matter under WHO thresholds and VOC concentrations at the more inland sampling points, does not differ in kind from the patterns reported in better-documented hydrocarbon communities nearby. Whether it differs in magnitude, and whether conditions change across seasons or over longer monitoring periods, cannot be answered from a single field campaign, and this is itself a finding: the absence of baseline data of this kind in coastal, non-flagship communities represents a genuine gap in the regional evidence base rather than an indication that such communities do not warrant monitoring.

ENVIRONMENTAL MANAGEMENT IMPLICATIONS

5.1 Regulatory and Monitoring Gaps

The tri-standard comparison in Section 4.2 points to a specific regulatory weakness rather than a general call for stricter enforcement. Nigeria's existing particulate matter thresholds, where they remain closer to older, more permissive limits than to current WHO guidance, provide little practical basis for identifying the kind of exposure documented at Belema, let alone the more widespread WHO-level exceedances recorded across the rest of the transect. A monitoring framework built solely around domestic thresholds would have concluded that air quality in four of the five sampled communities required no further attention. Closing this gap does not necessarily require replacing NESREA/FMEnv standards outright, but it does require regulators working in hydrocarbon-adjacent coastal communities to report against WHO or USEPA benchmarks alongside domestic ones, so that the scale of any discrepancy is visible to decision-makers rather than concealed by a single, more permissive figure.

5.2 Targeted Interventions for Hydrocarbon Coastal Communities

The spatial pattern identified in this study, elevated particulate matter concentrated at Belema and elevated VOC concentrations at the more inland locations, suggests that a single, kingdom-wide intervention would be less effective than site-specific measures. Studies of gas flare buffer zones elsewhere in the Niger Delta have proposed minimum separation distances between flare stacks and residential or agricultural land as a practical mitigation step once a point source is confirmed (Ehumadu et al., 2021), and a similar source-verification exercise at Belema, to confirm whether a flow station, generator cluster or another combustion activity is responsible for its particulate anomaly, would be a reasonable next step before any buffer or relocation measure is proposed. For the VOC-elevated inland locations, interventions aimed at reducing flaring intensity or improving vapour recovery at nearby facilities, where such facilities exist, are likely to have more direct effect than particulate-focused measures, which the data suggest are not the dominant concern at those specific sites.

5.3 Public Health Protection Measures

Belema's classification as Unhealthy for Sensitive Groups carries a specific and immediate implication: children, older residents and individuals with pre-existing respiratory conditions in that community face a materially different exposure profile than residents of the other four locations, and public health guidance issued at the kingdom level would understate the risk faced specifically in Belema. Community-level advisories, rather than a single blanket statement for Kula Kingdom as a whole, would more accurately reflect the exposure pattern this study has identified. More broadly, the elevated VOC readings recorded at Robert Kiri and Offoin-Ama warrant attention independent of the particulate finding, given the association documented elsewhere between VOC exposure and respiratory and other health outcomes in oil-producing Niger Delta communities (Wami-Amadi, 2025; Okoye et al., 2025).

CONCLUSION

This study assessed multi-pollutant ambient air quality across five coastal communities in Kula Kingdom, Rivers State, an area that has received little direct air quality attention despite lying within a hydrocarbon-producing corridor of the Niger Delta. Particulate matter, methane, volatile organic compounds, nitrogen dioxide, sulphur dioxide and ozone were measured at each location and benchmarked against WHO, USEPA and Nigerian regulatory standards. Belema recorded the highest particulate matter concentrations in the dataset and was the only location classified as Unhealthy for Sensitive Groups, while VOC concentrations were highest at the more inland locations of Robert Kiri and Offoin-Ama and declined toward the open Atlantic shoreline. Nitrogen dioxide followed a broadly opposite spatial pattern. Comparison against three regulatory standards showed that the apparent severity of pollution in Kula Kingdom depends considerably on which benchmark is applied, with WHO-based comparison identifying exceedances at every location while Nigeria's domestic standard identified none. Correlation analysis suggested that methane and VOCs share a common source signature distinct from that driving nitrogen dioxide concentrations, consistent with a mixed contribution from flaring-related and combustion-related sources reported elsewhere in the region, though the small number of sampling locations limits how firmly this can be concluded. Taken together, the findings close a portion of the data gap that has left coastal, non-flagship Niger Delta communities largely absent from the published air quality record, and they point toward the need for environmental management responses calibrated to specific locations rather than applied uniformly across the kingdom.

RECOMMENDATIONS

Based on the findings of this study, the following measures are recommended:

1. Establish continuous, or at minimum seasonally repeated, ambient air quality monitoring at the five Kula Kingdom locations sampled in this study, to determine whether the patterns observed persist across dry and wet seasons.

2. Investigate the specific source or sources of the particulate matter anomaly recorded at Belema, given its classification as Unhealthy for Sensitive Groups, before proposing any buffer distance or relocation measure.

3. Adopt WHO or USEPA benchmarks alongside domestic NESREA/FMEnv standards when reporting air quality in hydrocarbon-adjacent coastal communities, to avoid understating exposure relative to international guidance.

4. Prioritise flaring and vapour-recovery interventions at facilities near Robert Kiri and Offoin-Ama, where VOC concentrations were highest, rather than applying particulate-focused controls uniformly across the kingdom.

5. Issue community-specific, rather than kingdom-wide, public health guidance, given the materially different exposure classification recorded at Belema relative to the other four locations.

6. Extend future studies to include a wider set of coastal, non-flagship Niger Delta communities beyond the well-documented industrial hubs, to build a more representative regional baseline.

DECLARATIONS

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Declaration of Competing Interest

The author declares no conflict of interest regarding the publication of this research.

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Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

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