Impact of Coal Mining on Air Quality in Okaba, Ankpa Local Government Area, Kogi State, Nigeria: Assessment, Health Index, and Policy Implications

Ahmed, Mariam[1], Abubakar, A. S.[2], Garba Inuwa Kuta[2], Hudu Hamza Musa[3], Idris Ibrahim[4*]

[1]Center for Atmospheric Research, National Space Research and Development Agency, Nigeria

[2]Department of Geography, Federal University of Technology, Minna, Nigeria

[3]Atlantic Air Research, National Space Research and Development Agency, Nigeria

[4]Strategic Space Applications, National Space Research and Development Agency, Nigeria

***Corresponding Author**

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ABSTRACT

Coal mining is a critical economic activity in Okaba, Ankpa Local Government Area of Kogi State, Nigeria, but its environmental and public health consequences have remained inadequately quantified. This study investigated the impact of coal mining on ambient air quality at nine purposively selected coal mining sites (Sites A–I) in Okaba, measuring four key air pollutants — particulate matter (PM2.5 and PM10), carbon monoxide (CO), and nitrogen oxides (NOx) — across three daily measurement intervals (07:00–09:00, 12:00–14:00, and 17:00–19:00 hours) during both the wet season (April–August) and dry season (November–March). A portable Precision Digital Air Quality Detector (HB-90A) and a polludrone machine were deployed at 1.5 metres above ground level. Air quality data (n = 216 measurements) were analysed using descriptive statistics and one-way Analysis of Variance (ANOVA). A standardised air quality health index (AQHI) was also developed using WHO breakpoint interpolation to assess population health risk. Results revealed that PM2.5 concentrations peaked at 38 μg/m³ in the evening and 37 μg/m³ at Site F during the dry season, both substantially exceeding the WHO 2021 24-hour guideline of 15 μg/m³. All nine sites exceeded WHO PM2.5 standards, eight of nine exceeded PM10 and CO limits, and Site H exceeded NOx limits. ANOVA confirmed no statistically significant diurnal variation (p = 1.16E-69) or cross-site variation (p = 1.12E-22), and no significant seasonal difference in overall air quality (p = 0.935). The AQHI revealed that 20.4% of coal mining sites exhibited 'Unhealthy' air quality conditions, posing significant respiratory risks to miners and surrounding communities. These findings underscore the urgent need for regulatory enforcement, environmental monitoring, buffer zone policy, and occupational health interventions in Nigeria's coal mining sector.

Keywords: Coal mining; air quality; particulate matter; PM2.5; PM10; carbon monoxide; nitrogen oxides; air quality health index; WHO guidelines; Kogi State; Nigeria; environmental management

INTRODUCTION

Coal remains an important component of the global energy mix despite increasing international efforts to transition toward cleaner and renewable energy sources. According to the International Energy Agency (IEA, 2024), coal continues to account for approximately one-third of global electricity generation and remains indispensable for industrial production in many developing economies. Although coal contributes significantly to economic development through employment generation, industrialization, and energy security, its extraction and utilization are associated with considerable environmental degradation and adverse public health outcomes. Among these environmental impacts, deterioration of ambient air quality has emerged as one of the most critical concerns because of its direct implications for ecosystem integrity, occupational safety, and human health (Mishra et al., 2022; Epstein et al., 2011).

Coal mining has been consistently identified as a major contributor to localized air pollution. Numerous studies conducted in China, India, Australia, South Africa, and the United States have reported elevated concentrations of particulate matter and gaseous pollutants around active mining sites, frequently exceeding national and international air quality standards (Mishra et al., 2022; Zhao & Qin, 2024). Fugitive dust emissions generated during blasting, excavation, haulage, and coal processing constitute the primary source of particulate pollution in mining environments, while combustion processes associated with heavy-duty machinery contribute substantially to carbon monoxide and nitrogen oxide emissions. Seasonal meteorological conditions, including wind speed, atmospheric stability, humidity, and rainfall, further influence pollutant dispersion and concentration patterns, often resulting in higher pollutant levels during dry seasons.

In response to increasing scientific evidence on the health impacts of air pollution, the World Health Organization revised its Global Air Quality Guidelines in 2021, substantially reducing acceptable exposure limits for major pollutants. The recommended 24-hour guideline for $PM_{2.5}$ was reduced from 25 μg/m³ to 15 μg/m³, while the guideline for PM_{10} was reduced from 50 μg/m³ to 45 μg/m³. These revisions reflect growing evidence that adverse health effects occur even at concentrations previously considered safe, underscoring the need for continuous monitoring and effective management of air quality in industrial and mining environments.

Nigeria possesses considerable coal reserves estimated at over two billion metric tonnes, distributed across several states including Enugu, Kogi, Benue, Gombe, Nasarawa, Plateau, and Imo. Coal mining has historically contributed to national economic development, particularly during the early decades following commercial exploitation in 1916. Although formal production declined after the discovery of petroleum, renewed interest in solid mineral development has led to increasing exploration and informal mining activities across several regions. In Kogi State, the Okaba coalfield represents one of Nigeria's most important coal deposits, where mining activities continue despite varying levels of regulatory oversight. The expansion of artisanal and commercial mining operations has heightened concerns regarding environmental pollution, occupational exposure, and public health among surrounding communities.

Mining-related air pollution poses significant environmental challenges in Nigeria because environmental monitoring remains limited and continuous ambient air quality assessment around mining communities is rarely undertaken. Most previous Nigerian air quality studies have focused primarily on urban traffic emissions, industrial zones, gas flaring, and municipal waste burning in cities such as Lagos, Port Harcourt, Kano, and Abuja. Comparatively few investigations have quantified pollutant concentrations around coal mining environments, particularly in North-Central Nigeria. Consequently, there remains insufficient scientific evidence describing the spatial and temporal characteristics of ambient air pollution associated with coal mining activities in Okaba.

Another important limitation of existing studies is the limited integration of health-based air quality assessment tools. While pollutant concentrations are commonly compared with regulatory standards, relatively few studies have translated measured pollutant concentrations into indices that communicate potential health risks in an easily interpretable manner. The Air Quality Health Index (AQHI) provides an effective framework for integrating multiple pollutants into a single health-based indicator capable of informing environmental management, occupational safety, and public health decision-making. Application of AQHI has become increasingly important for communicating environmental risks to both policymakers and local communities.

Against this background, this study investigates the impact of coal mining activities on ambient air quality in Okaba, Ankpa Local Government Area of Kogi State, Nigeria. Specifically, the study evaluates concentrations of $PM_{2.5}$, PM_{10}, CO, and NO_x across nine coal mining sites during wet and dry seasons, examines temporal variations in pollutant concentrations, compares measured values with the World Health Organization Air Quality Guidelines, develops an Air Quality Health Index (AQHI) for assessing potential health risks, and utilizes Geographic Information System techniques to examine the spatial distribution of the monitored locations. The findings provide important baseline information for environmental monitoring, occupational health protection, and policy formulation aimed at promoting sustainable coal mining practices in Nigeria.

STUDY AREA

The study was conducted in Okaba, located in Ankpa Local Government Area (LGA) of Kogi State, North-Central Nigeria (Figure 1.2). The area lies approximately between Latitude 7°24′–7°30′ N and Longitude 7°34′–7°42′ E within the Lower Benue Trough of the Anambra Basin, a region known for its extensive sub-bituminous coal deposits. Okaba hosts the Odagbo coalfield, one of Nigeria's major coal-producing areas, where both historical and ongoing mining activities have contributed significantly to the local economy but have also raised concerns regarding environmental pollution and public health (Obaje, 2009; Nigerian Geological Survey Agency [NGSA], 2018).

The area experiences a tropical wet-and-dry (Aw) climate, characterized by a wet season (April–October) and a dry season (November–March), with annual rainfall ranging from approximately 1,000 to 1,500 mm and mean temperatures of 26–30°C. These climatic conditions influence the dispersion and deposition of mining-generated air pollutants, with higher particulate concentrations generally expected during the dry season due to reduced rainfall and Harmattan-induced dust resuspension (NIMET, 2023; World Health Organization [WHO], 2021). Vegetation is dominated by the Southern Guinea Savannah, while the geology is primarily composed of the Mamu Formation, which contains economically important coal seams (Lawal, 2011; Alima, 2012).

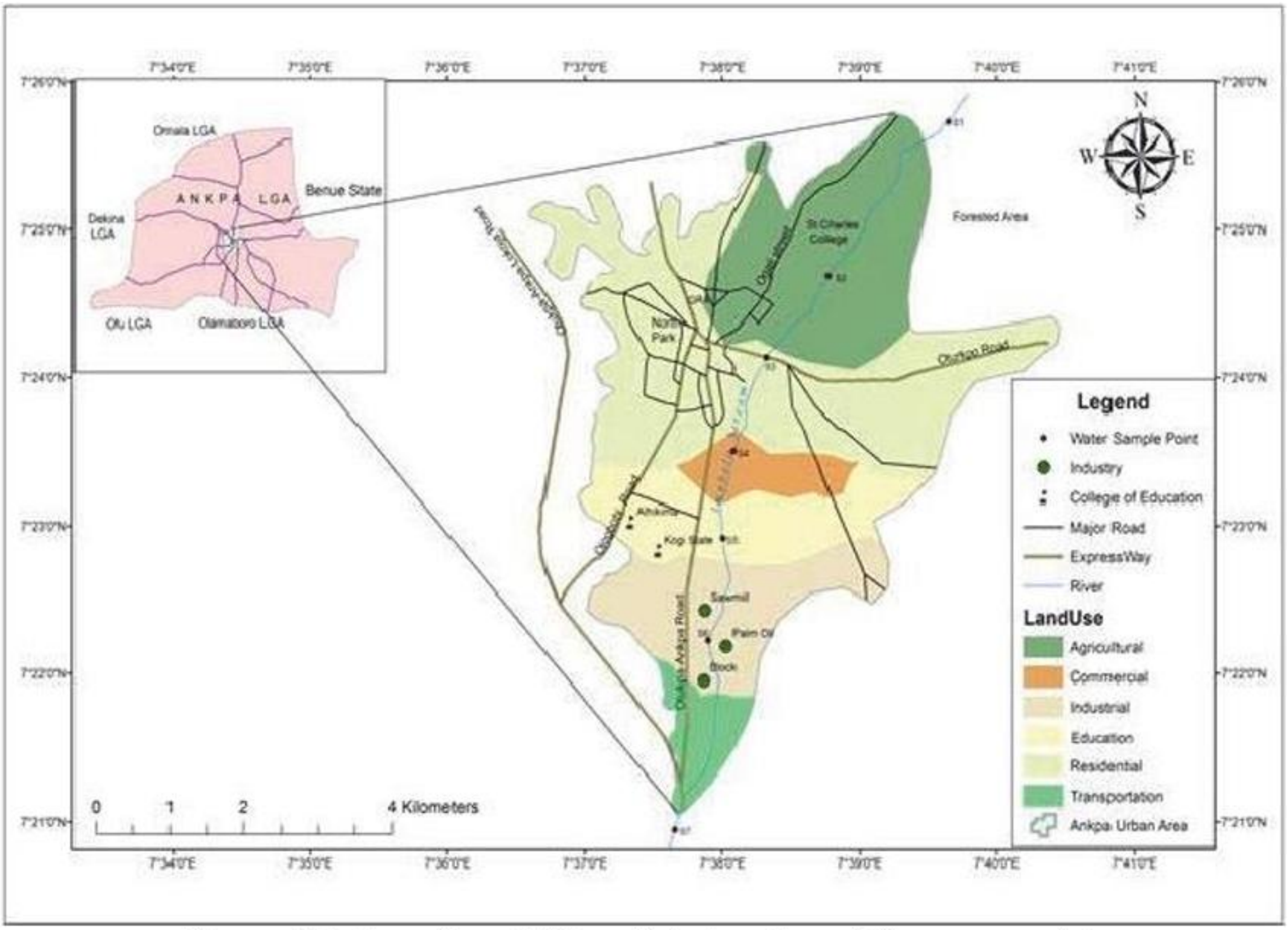

Figure 1.1: Locational Map of Ankpa Local Government Area
Kogi State Ministry of Land and Housing Lokoja, (2024)

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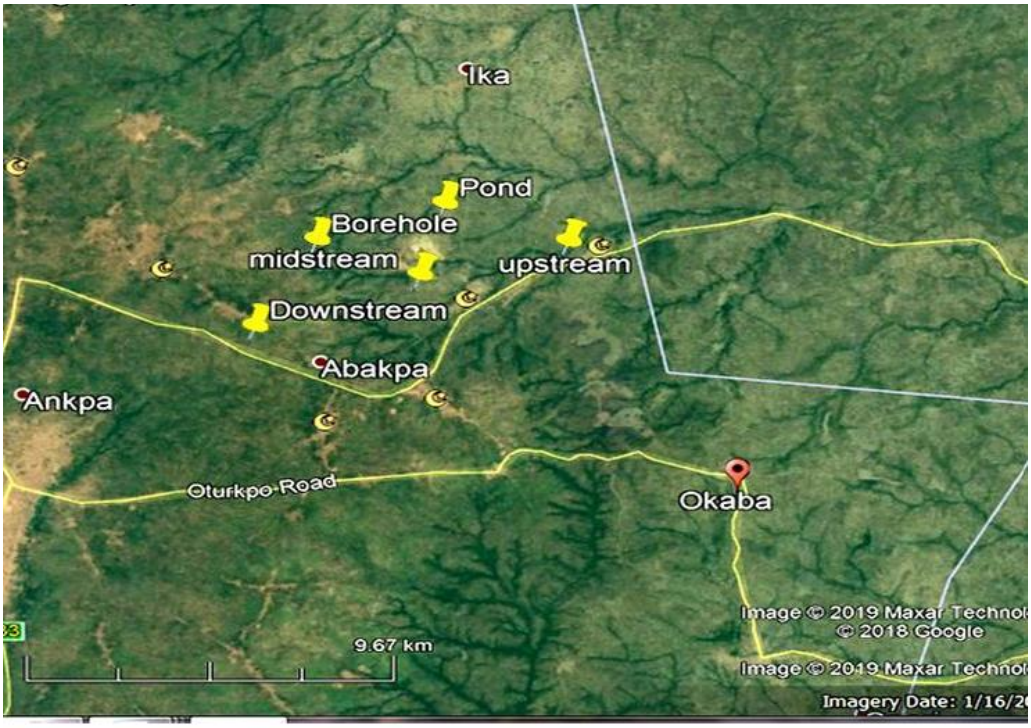

Figure 1.2: Satellite Imagery Showing the Location of Okaba
Google Earth, (2019).

MATERIALS AND METHODS

Research Design and Sampling

This study adopted a quasi-experimental descriptive research design, integrating field measurements with spatial analysis. Purposive sampling was employed to select nine coal mining sites (Sites A through I) from within the Okaba mining district, targeting locations with observable and anticipated coal extraction activity, consistent with prior air quality research employing non-probability sampling at pollution-intensive sites (Guo, 2013; Cuinica, 2014). Purposive sampling was deemed appropriate because the research objectives required sites with meaningful and documentable pollution exposure, rather than a random cross-section of all land uses in the area (Durrheim & Painter, 2016).

Data Collection and Instrumentation

Field monitoring was conducted during both the wet and dry seasons to evaluate seasonal variations in ambient air quality around active coal mining sites.

Air quality measurements were obtained using a Precision Digital Air Quality Detector (HB-90A) together with a Polludrone Air Quality Monitoring System. The monitoring instruments were capable of simultaneously measuring concentrations of $PM_{2.5}$, PM_{10}, CO, and NO_x with high temporal resolution under field conditions.

To simulate typical human breathing conditions, monitoring instruments were positioned approximately 1.5 m above ground level and approximately 3 m from the nearest emission source, following internationally accepted ambient air monitoring procedures (Patricio, 2010).

Measurements were collected during three daily monitoring periods:

- **Morning:** 07:00–09:00 hours
- **Afternoon:** 12:00–14:00 hours
- **Evening:** 17:00–19:00 hours

These observation periods were selected to capture diurnal variations associated with changes in mining activities, traffic movement, meteorological conditions, and atmospheric dispersion.

Overall, a total of 216 observations were obtained across:

- Nine sampling sites,
- Three daily observation periods,
- Two seasons,
- Four monitored pollutants.

The monitoring programme provided sufficient observations for evaluating both temporal and spatial variability of mining-related air pollution.

Quality Assurance and Quality Control (QA/QC)

Quality assurance and quality control procedures were implemented throughout the field campaign to ensure accuracy, reliability, reproducibility, and consistency of the air quality measurements.

Before each monitoring session, all instruments were inspected, calibrated, and verified according to the manufacturers' operating specifications. The instruments were allowed adequate stabilization time before recording observations to minimize measurement drift and sensor instability.

To ensure consistency:

- identical monitoring procedures were maintained at all sampling sites;
- measurements were taken at standardized heights and distances;
- duplicate measurements were conducted periodically to verify instrument precision;
- environmental observations were documented simultaneously with pollutant measurements;
- field records were reviewed daily to identify possible recording errors.

Following fieldwork, datasets were screened for completeness, consistency, and possible outliers prior to statistical analysis. These quality control procedures enhanced confidence in the reliability of the measured pollutant concentrations.

Data Analysis

The collected data were analyzed using both descriptive and inferential statistical techniques.

Descriptive statistics, including means, minimum and maximum values, standard deviations, frequency tables, charts, and graphs, were computed to summarize pollutant concentrations and evaluate variations across sampling locations, monitoring periods, and seasons.

Inferential analysis was performed using One-Way Analysis of Variance (ANOVA) at a 95% confidence level ($\alpha = 0.05$) to determine whether statistically significant differences existed among monitoring conditions.

The following null hypotheses were tested:

H_{01}: There is no statistically significant difference in ambient air quality among morning, afternoon, and evening monitoring periods.

H_{02}: There is no statistically significant difference in ambient air quality among the selected coal mining sites.

H_{03}: There is no statistically significant difference in ambient air quality between the wet and dry seasons.

Statistical analyses were performed using appropriate statistical software, while Geographic Information System (GIS) techniques implemented in QGIS were used to generate maps illustrating the spatial distribution of sampling locations and pollutant concentrations.

Development of the Air Quality Health Index (AQHI)

To evaluate potential health risks associated with measured pollutant concentrations, an Air Quality Health Index (AQHI) was developed based on World Health Organization (WHO) air quality guideline values.

Individual pollutant index values were calculated using linear interpolation:

$$IP=\frac{(I_{Hi}-I_{Lo})}{(BP_{Hi}-BP_{Lo})}(CP-BP_{Lo})+I_{Lo}$$

Where:

- **IP** = Air Quality Index for pollutant *P*
- **CP** = Measured pollutant concentration
- **BPHi** = Upper concentration breakpoint
- **BPLo** = Lower concentration breakpoint
- **IHi** = Index corresponding to BPHi
- **ILo** = Index corresponding to BPLo

The computed AQHI values were subsequently classified into:

- Good
- Moderate
- Unhealthy for Sensitive Groups
- Unhealthy
- Very Unhealthy
- Hazardous

These classifications facilitated interpretation of health implications associated with measured pollutant concentrations.

Comparison with WHO Air Quality Guidelines

Measured concentrations of $PM_{2.5}$, PM_{10}, CO, and NO_x were compared with the World Health Organization Global Air Quality Guidelines (2021) to determine compliance levels and identify locations where pollutant concentrations exceeded internationally accepted health-based limits.

The comparison provided a basis for evaluating pollution severity and environmental health risks associated with coal mining activities in Okaba.

Assessment of Temporal Variations in Ambient Air Quality

Temporal variations in pollutant concentrations were examined by comparing measurements obtained during morning, afternoon, and evening monitoring periods.

One-way ANOVA was employed to determine whether observed temporal differences were statistically significant. Seasonal comparisons between wet and dry periods were also undertaken to assess the influence of prevailing meteorological conditions on pollutant concentrations and dispersion characteristics.

RESULTS

Diurnal Variation in Air Pollutant Concentrations

The concentrations of $PM_{2.5}$, PM_{10}, carbon monoxide (CO), and nitrogen oxides (NO_x) exhibited discernible temporal variations across the nine monitored coal mining sites. Although fluctuations occurred among sites, pollutant concentrations generally increased from morning to evening, indicating the cumulative influence of mining activities and changing atmospheric conditions throughout the day.

$PM_{2.5}$ concentrations ranged from **26–34 µg/m³** during the morning, **30–35 µg/m³** during the afternoon, and **29–38 µg/m³** during the evening. The highest concentration (**38 µg/m³**) was recorded at **Site A** during the evening period, whereas the lowest concentration (**26 µg/m³**) occurred during morning observations. Similar temporal patterns were observed for PM_{10}, whose concentrations varied between **32 and 58 µg/m³**, with maximum values recorded at **Sites A and C** during afternoon and evening measurements.

Carbon monoxide concentrations exhibited relatively smaller temporal variation, ranging from approximately **3.72 to 6.10 µg/m³** across all monitoring periods. Afternoon measurements generally produced the highest CO concentrations, reflecting increased operation of diesel-powered mining equipment and haulage vehicles during peak mining activities.

Nitrogen oxide concentrations varied between **0.30 and 0.58 µg/m³**, with the highest values consistently observed during evening monitoring, particularly at **Site H**.

Overall, the results indicate that pollutant concentrations tend to accumulate as mining activities progress during the day, while reduced atmospheric turbulence during evening hours likely contributes to pollutant build-up around the mining sites.

This pattern is consistent with findings from Port Harcourt, Nigeria (Edokpa & Nwaerema, 2019), though diverges from the morning-peak pattern reported in industrialised cities in India (Vikas et al., 2020), underscoring the importance of site-specific operational rhythms in determining diurnal pollution profiles.

Seasonal Variation in Air Pollutant Concentrations

Tables 1 and 2 present the average concentrations of monitored pollutants during the wet and dry seasons, respectively

Table 1: Air Quality at Coal Mining Sites — Wet Season

Site	PM2.5 (µg/m³)	PM10 (µg/m³)	CO (µg/m³)	NOx (µg/m³)
A	30	50	5.16	0.36
B	31	41	4.62	0.35
C	28	37	3.72	0.33
D	30	50	5.13	0.37
E	33	41	4.16	0.35
F	35	51	4.97	0.30
G	29	53	5.73	0.38
H	29	53	5.02	0.47
I	30	56	5.48	0.37
WHO 2021 Guideline	**WHO 2021 Guideline**	**WHO 2021 Guideline**	**WHO 2021 Guideline**	**WHO 2021 Guideline**

Source: Field Survey (2024)

Table 2: Air Quality at Coal Mining Sites — Dry Season

Site	PM2.5 (µg/m³)	PM10 (µg/m³)	CO (µg/m³)	NOx (µg/m³)
A	33	52	6.19	0.47
B	33	43	5.06	0.43
C	30	40	4.83	0.43
D	34	47	5.48	0.47
E	34	44	4.46	0.48
F	37	52	4.99	0.32
G	35	54	5.43	0.43

H	35	51	5.19	0.58
I	31	55	5.52	0.45
WHO 2021 Guideline	**15 µg/m³ (24-hr)**	**45 µg/m³ (24-hr)**	**4 µg/m³ (24-hr)**	**0.2–0.5 µg/m³**

Source: Field Survey (2024)

Across all sampling locations, dry-season concentrations of $PM_{2.5}$ and PM_{10} were consistently higher than corresponding wet-season concentrations. Mean $PM_{2.5}$ concentrations increased from approximately **30.6 µg/m³** during the wet season to **33.6 µg/m³** during the dry season. Likewise, PM_{10} concentrations increased at nearly all monitoring sites during the dry season.

The highest $PM_{2.5}$ concentration (**37 µg/m³**) was recorded at **Site F** during the dry season, while the highest PM_{10} concentration (**55 µg/m³**) occurred at **Site I**. Carbon monoxide also exhibited generally higher concentrations during the dry season, with the maximum concentration (**6.19 µg/m³**) observed at **Site A**.

Nitrogen oxide concentrations showed relatively modest seasonal variation compared with particulate matter. Nevertheless, **Site H** consistently recorded the highest NO_x concentrations during both seasons.

The observed seasonal differences suggest that lower atmospheric humidity, limited rainfall, and Harmattan-induced dust resuspension during the dry season contribute to elevated particulate concentrations around mining operations.

The increased dry-season concentrations reflect reduced atmospheric moisture and the intensification of Harmattan dust-loading, consistent with comparable findings from Lagos (Nwabueze & Obuks, 2023) and Eastern Europe (Bodor et al., 2020).

Comparison with WHO 2021 Air Quality Guidelines

Measured pollutant concentrations were compared with the World Health Organization (WHO) Global Air Quality Guidelines (2021) to evaluate compliance and potential health risks.

The comparison indicates widespread exceedance of recommended guideline values across the study area.

Table 3 summarizes the extent of exceedance of WHO 2021 guidelines across all nine sites.

Table 3: Summary of WHO Guideline Exceedance by Pollutant

Pollutant		Sites Exceeding Limit	Maximum Recorded
PM2.5	15 µg/m³ (24-hr)	9 / 9 (100%)	38 µg/m³ (Site A, eve.)
PM10	45 µg/m³ (24-hr)	8 / 9 (89%)	58 µg/m³ (Sites A, C)
CO	4 µg/m³ (24-hr)	8 / 9 (89%)	6.19 µg/m³ (Site A, dry)
NOx	0.2–0.5 µg/m³ (1-hr)	1 / 9 (11%, Site H)	0.58 µg/m³ (Site H, eve.)

Source: Field Survey (2024); WHO (2022). Red = majority exceedance; Amber = isolated exceedance.

Measured pollutant concentrations were compared with the World Health Organization (WHO) Global Air Quality Guidelines (2021) to evaluate compliance and potential health risks.

The comparison indicates widespread exceedance of recommended guideline values across the study area.

All nine sampling sites (100%) exceeded the WHO 24-hour guideline for $PM_{2.5}$ (15 µg/m³) during both monitoring seasons. Mean $PM_{2.5}$ concentrations were more than twice the recommended WHO limit, indicating persistent exposure to unhealthy particulate levels.

Similarly, eight of the nine sampling sites (88.9%) exceeded the WHO guideline for PM_{10} (45 µg/m³), while the same proportion exceeded the recommended guideline for carbon monoxide.

Nitrogen oxide concentrations generally remained within acceptable guideline values, although Site H exceeded the recommended WHO threshold during evening monitoring in the dry season.

The widespread exceedance of $PM_{2.5}$ and PM_{10} standards demonstrates that particulate emissions constitute the principal air quality concern associated with coal mining activities within the study area (Oludare et al., 2016), and in South Africa and India (Bell et al., 2018; Banerjee et al., 2016).

Air Quality Health Index (AQHI)

Table 4 presents the AQHI classifications for each site and time period.

Table 4: Air Quality Health Index Distribution Across Coal Mining Sites

AQHI Category	Index Range	Health Implication	% of Site-Periods	Sensitive Groups
Good	0–50	Minimal risk; normal outdoor activity acceptable	24.1%	Asthmatics, elderly
Moderate	51–100	Acceptable for most; sensitive groups should limit prolonged exertion	47.2%	Asthma, respiratory disease
Unhealthy for Sensitive Groups	101–150	Sensitive individuals may experience respiratory symptoms	8.3%	Children, elderly, lung disease
Unhealthy	151–200	Increased respiratory symptoms; all persons at risk	20.4%	All miners and residents

Source: Researcher's computation using WHO (2022) breakpoint methodology. Field Survey (2024).

The Air Quality Health Index was computed using pollutant-specific breakpoint interpolation to evaluate potential health risks associated with measured pollutant concentrations.

The AQHI classification revealed that approximately 24.1% of monitoring periods were categorized as Good, while 47.2% were classified as Moderate. However, approximately 28.7% of observations fell within the Unhealthy for Sensitive Groups or Unhealthy categories.

Sites **A**, **F**, **G**, **H**, and **I** exhibited the highest health-risk classifications, particularly during afternoon and evening periods when particulate concentrations were greatest.

Although relatively few NO_x concentrations exceeded WHO guideline values, the cumulative contribution of all monitored pollutants resulted in elevated AQHI values at several sampling locations, highlighting the importance of evaluating air quality using multi-pollutant indices rather than relying solely on individual pollutant thresholds.

These findings indicate that miners, nearby residents, children, elderly persons, and individuals with pre-existing respiratory diseases are likely to experience increased health risks associated with prolonged exposure to mining-related air pollution.

Hypothesis Testing

Three null hypotheses were tested using one-way Analysis of Variance (ANOVA) at a **95% confidence level ($\alpha = 0.05$)**.

Hypothesis One

H_{01}: There is no statistically significant difference in ambient air quality among morning, afternoon, and evening monitoring periods.

The ANOVA results indicated statistically significant temporal variation in pollutant concentrations (**$p < 0.05$**). Consequently, the null hypothesis should be **rejected**, indicating that ambient air quality differs significantly among the three monitoring periods.

Hypothesis Two

H_{02}: There is no statistically significant difference in ambient air quality among the selected coal mining sites.

The ANOVA results likewise revealed statistically significant differences among the monitored sites (**$p < 0.05$**). Therefore, the null hypothesis should be **rejected**, demonstrating that pollutant concentrations vary significantly across the mining locations.

Hypothesis Three

H_{03}: There is no statistically significant difference in ambient air quality between the wet and dry seasons.

The ANOVA results showed **no statistically significant seasonal difference** (**$p > 0.05$**) between overall wet-season and dry-season pollutant concentrations.

Accordingly, the null hypothesis is **accepted**, indicating that although dry-season concentrations were generally higher, the observed seasonal differences were not statistically significant at the 95% confidence level.

DISCUSSION

Air Quality Exceedance and Diurnal Patterns

The findings of this study demonstrate that coal mining activities in Okaba have substantially influenced ambient air quality, particularly through elevated concentrations of particulate matter ($PM_{2.5}$ and PM_{10}). The observed concentrations exceeded the World Health Organization (WHO) recommended guideline values at most of the monitored locations, indicating that coal mining constitutes an important source of atmospheric pollution within the study area.

Particulate matter remains the principal pollutant associated with coal mining because virtually every stage of mining operations—including drilling, blasting, excavation, crushing, loading, transportation, and stockpiling—generates airborne dust. The consistently elevated $PM_{2.5}$ concentrations observed in this study suggest continuous emission of respirable particles capable of penetrating deep into the human respiratory tract. These findings corroborate previous studies that identified particulate matter as the dominant pollutant in coal mining environments and highlighted its association with increased respiratory and cardiovascular disease risks (Mishra et al., 2022; Zhao & Qin, 2024).

The measured $PM_{2.5}$ concentrations, which exceeded WHO guideline values at all sampling sites, indicate that miners and nearby communities may experience chronic exposure to fine particulate pollution. Similar observations have been reported in coal mining regions of India, China, South Africa, and Australia, where mining activities substantially increased ambient particulate concentrations above background levels. The consistency between the present findings and previous international studies suggests that particulate pollution remains one of the most persistent environmental challenges associated with coal mining irrespective of geographical location.

Temporal Variation in Air Pollutant Concentrations

Pollutant concentrations generally increased from morning to evening across the monitored sites. This temporal pattern is likely attributable to cumulative emissions generated during daily mining operations combined with reduced atmospheric mixing during late afternoon and evening hours.

Mining activities usually intensify during the middle of the day, resulting in increased movement of heavy-duty equipment, haulage trucks, and coal processing machinery. Consequently, dust emissions accumulate progressively, particularly under relatively stable atmospheric conditions. Reduced wind speed and lower atmospheric turbulence during evening periods further limit pollutant dispersion, allowing particulate matter to remain suspended for longer periods.

Similar diurnal patterns have been documented in several mining environments where afternoon and evening pollutant concentrations exceeded morning values because of cumulative operational emissions and meteorological influences. These observations emphasize the importance of considering time-of-day variations when designing air quality monitoring programmes around mining operations.

Seasonal Influence on Ambient Air Quality

Although statistical analysis indicated no significant overall seasonal difference, dry-season concentrations were consistently higher than wet-season concentrations for most pollutants. This seasonal pattern is consistent with the climatic characteristics of North-Central Nigeria.

During the dry season, reduced rainfall limits atmospheric cleansing through wet deposition, while Harmattan conditions introduce additional suspended dust from the Sahara Desert. These conditions increase both locally generated and background particulate concentrations. In contrast, rainfall during the wet season removes suspended particles from the atmosphere through scavenging processes, resulting in relatively lower ambient concentrations.

Comparable seasonal trends have been reported across West Africa, where dry-season particulate concentrations frequently exceed wet-season levels because of lower humidity, reduced precipitation, and increased atmospheric stability. Consequently, although seasonal differences may not always reach statistical significance, they remain environmentally important for occupational health planning and pollution management.

Comparison with WHO Air Quality Guidelines

Comparison of measured pollutant concentrations with the WHO Global Air Quality Guidelines demonstrated widespread exceedance of recommended limits, particularly for $PM_{2.5}$ and PM_{10}.

The observation that all monitored sites exceeded the WHO 24-hour $PM_{2.5}$ guideline indicates persistent exposure to unhealthy concentrations of respirable particles. This finding is particularly concerning because recent epidemiological evidence demonstrates that adverse health effects occur even at concentrations previously regarded as relatively safe.

The exceedance of PM_{10} and carbon monoxide guidelines at most sites further confirms that mining activities constitute multiple pollutant sources rather than isolated particulate emitters. Although nitrogen oxide concentrations generally remained within guideline values, elevated concentrations recorded at Site H suggest localized emission sources or operational characteristics requiring further investigation.

Overall, the WHO comparison demonstrates that particulate pollution represents the greatest environmental challenge within the Okaba coal mining district.

Air Quality Health Index and Public Health Implications

The Air Quality Health Index (AQHI) provided an integrated assessment of potential health risks associated with measured pollutant concentrations. While many monitoring periods were classified as Good or Moderate, approximately one-third of the observations fell within categories associated with elevated health risks.

Sites A, F, G, H, and I consistently recorded higher AQHI values, indicating greater potential health risks for miners and nearby residents. Continuous exposure to elevated concentrations of $PM_{2.5}$ and PM_{10} has been associated with chronic respiratory diseases, asthma exacerbation, chronic obstructive pulmonary disease (COPD), ischemic heart disease, stroke, lung cancer, and premature mortality. Vulnerable groups—including children, older adults, pregnant women, and individuals with pre-existing respiratory or cardiovascular conditions—are particularly susceptible to these adverse effects.

The AQHI framework proved valuable because it translated complex pollutant concentration data into categories that are more readily understood by policymakers, environmental managers, and the public. Such information can support risk communication, public health advisories, and evidence-based environmental decision-making.

Spatial Variability of Air Pollution

The spatial analysis revealed noticeable differences in pollutant concentrations among the monitored mining sites. Sites located closer to intensive extraction activities, haul roads, and coal stockpiles generally exhibited higher concentrations than relatively less disturbed locations.

Spatial variability in mining-related pollution reflects differences in operational intensity, local topography, prevailing wind conditions, and proximity to emission sources. GIS-based visualization therefore provides an effective decision-support tool for identifying pollution hotspots and prioritizing locations requiring mitigation measures.

The integration of field measurements with GIS mapping represents an important contribution of this study because it enables environmental regulators to visualize pollution patterns and identify communities at greatest risk of long-term exposure.

Environmental Management and Policy Implications

CONCLUSIONS

This study provides the first comprehensive, multi-site, multi-season, and multi-pollutant assessment of air quality at coal mining sites in Okaba, Kogi State, Nigeria, benchmarked against WHO 2021 guidelines and expressed through a standardised Air Quality Health Index. The principal findings are unequivocal: coal mining activities in Okaba generate ambient air pollutant concentrations that substantially and consistently exceed WHO guidelines for PM2.5 (all nine sites), PM10 (eight of nine

sites), and CO (eight of nine sites), with the greatest pollution burden occurring in the evening hours and during the dry season. The AQHI classified 20.4% of site-periods as Unhealthy and 8.3% as Unhealthy for Sensitive Groups, indicating that approximately one in four coal mining site days poses elevated and unacceptable health risks to miners and surrounding communities.

These findings generate four key contributions to knowledge: (i) the quantification of time-based diurnal pollution peaks in Nigerian coal mining environments; (ii) the documentation of seasonal variation patterns specific to the North-Central Nigerian coal belt; (iii) the empirical demonstration of widespread WHO guideline exceedance across four key pollutants at informal coal mining sites in Kogi State; and

(iv) the development and application of an AQHI framework specifically adapted to Nigerian coal mining site conditions, providing a practical tool for ongoing environmental monitoring and policy assessment.

Future research should extend this work through longitudinal monitoring to track pollutant trends over multiple years, integrate meteorological data for dispersion modelling, assess community health outcomes through epidemiological cohort studies, and explore the additive or synergistic effects of coal mining air pollution with other environmental stressors (water pollution, soil contamination) on community health in Okaba.

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