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Assessing Spatial Distribution of Cement-Dust Pollution and Respiratory Health Indicators in Enugu Metropolis, Nigeria: A Preliminary Ecological Assessment

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Abstract: Rapid urbanization and increasing construction activities have contributed to growing concerns regarding ambient particulate pollution and its potential implications for public health in developing cities. This study assessed the spatial distribution of cement-dust-related pollutants and examined respiratory health indicators in Enugu Metropolis, southeastern Nigeria. Ambient air samples were collected from twenty-two residential estates between March and September 2023 using a MiniVol portable air sampler and a Bosean multi-gas detector. Concentrations of $PM_{2.5}$, PM_{10}, SO_2, and cement-associated oxides, including silica (SiO_2), iron oxide (Fe_2O_3), aluminum oxide (Al_2O_3), magnesium oxide (MgO), potassium oxide (K_2O), and sodium oxide (Na_2O), were determined. Geographic Information System (GIS) interpolation techniques were employed to characterize spatial distribution patterns, while tuberculosis (TB) records obtained from the Enugu State Ministry of Health were used as respiratory health indicators at the Local Government Area (LGA) level. Results showed mean $PM_{2.5}$ and PM_{10} concentrations of 26.59 $\mu g\ m^{-3}$ and 34.41 $\mu g\ m^{-3}$, respectively. PM_{10} concentrations generally complied with international and national standards, whereas $PM_{2.5}$ concentrations slightly exceeded World Health Organization guideline values at selected locations. GIS analyses revealed localized pollutant hotspots around Heliu Estate, Harmony Estate, Fidelity Estate, Goshen Estate, Jubilee Estate, and Sunrise Estate, suggesting the influence of construction activities, traffic emissions, and dust resuspension. Health records indicated a total of 390 reported tuberculosis cases within Enugu Urban during 2023, with the highest burden occurring in Enugu West Local Government Area. Because environmental and health datasets were available at different spatial scales, the study was designed as a preliminary ecological assessment rather than a causal epidemiological investigation. Consequently, direct exposure-response relationships could not be established. Nevertheless, the findings provide valuable baseline information on urban air quality and respiratory health indicators and highlight the need for integrated environmental-health monitoring systems, improved dust-control measures, and sustainable urban planning in rapidly developing cities.

Keywords: Cement dust pollution; $PM_{2.5}$; PM_{10}; Geographic Information System; Respiratory health indicators; Tuberculosis; Enugu Metropolis; Ecological assessment.

1. Introduction

Air pollution remains one of the most significant environmental challenges affecting public health worldwide. Among the various pollutants contributing to deteriorating air quality, particulate matter (PM) has received considerable attention because of its ability to penetrate the respiratory system and induce adverse health effects. Fine particulate matter, particularly particles with aerodynamic diameters less than 2.5 μm ($PM_{2.5}$) and 10 μm (PM_{10}), has been associated with respiratory and cardiovascular diseases, reduced lung function, increased hospital admissions, and premature mortality [1–3]. Rapid urbanization and expanding construction activities in developing countries have heightened concerns regarding ambient particulate pollution and its implications for environmental health [4].

Cement is one of the most widely used construction materials globally and plays a critical role in infrastructure development. However, the production, transportation, storage, and handling of cement generate substantial quantities of airborne dust. Cement dust consists primarily of calcium oxide (CaO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), ferric oxide (Fe_2O_3), magnesium oxide (MgO), potassium oxide (K_2O), and sodium oxide (Na_2O), many of which can become airborne during construction operations and material handling activities [5]. These particles may remain suspended in the atmosphere for extended periods and contribute to ambient particulate pollution, particularly in rapidly developing urban environments.

Previous studies have demonstrated that occupational and environmental exposure to cement dust may adversely affect respiratory health. Investigations conducted in cement-producing regions of Nigeria and other developing countries have reported elevated particulate concentrations and respiratory symptoms among workers and nearby residents [6–10]. Merenu et al. [6] reported reduced lung function among residents living near cement-production facilities in Sokoto State, while Chukwu and Ubosi [7] documented respiratory impairment among workers exposed to cement dust in Ewekoro, Nigeria. Similar observations have been reported among exposed populations in Saudi Arabia, Pakistan, and Ethiopia [8–10]. These findings suggest that prolonged exposure to cement-related particulate matter may contribute to respiratory-health risks, particularly among vulnerable populations.

Despite increasing attention to cement-dust pollution, most studies have focused on communities located near cement-manufacturing facilities [20–25]. Comparatively little attention has been given to urban environments where cement is not produced but is extensively utilized in residential and commercial construction projects. In such environments, particulate emissions arise primarily from construction activities, material transportation, storage, excavation, earthworks, and traffic-related dust resuspension. These diffuse sources can collectively contribute to ambient particulate pollution even in the absence of major industrial emitters.

Enugu Metropolis, located in southeastern Nigeria, provides an appropriate setting for examining this issue. The metropolis has experienced substantial population growth and urban expansion over the past two decades. Numerous residential estates, commercial developments, road projects, and public infrastructure improvements have been undertaken throughout the city. Although no major cement-manufacturing facilities operate within the metropolis, construction-related activities occur extensively across the study area. Consequently, significant quantities of cement dust and associated particulates may be released into the environment, potentially affecting ambient air quality.

Respiratory diseases continue to represent a major public-health concern globally and within Nigeria. Tuberculosis (TB), pneumonia, chronic bronchitis, asthma, and other lower respiratory tract infections contribute substantially to morbidity and mortality, particularly in developing countries [11,12]. According to the World Health Organization, tuberculosis remains one of the leading infectious causes of death worldwide and continues to impose significant health burdens across sub-Saharan Africa [26]. Importantly, tuberculosis is caused by *Mycobacterium tuberculosis* and cannot be attributed directly to environmental particulate pollution. However, environmental stressors such as airborne particulate matter may impair respiratory defense mechanisms, exacerbate pulmonary irritation, and potentially increase susceptibility among exposed populations [13,14].

The relationship between air pollution and respiratory disease is complex and influenced by numerous confounding factors. Variables such as smoking habits, indoor biomass-fuel use, occupational exposure, socioeconomic status, housing conditions, population density, nutrition, healthcare accessibility, and meteorological conditions may independently affect respiratory-health outcomes [14]. Consequently, environmental-health investigations must be interpreted cautiously, particularly when epidemiological and environmental datasets are collected at different spatial or temporal scales.

Recent advances in environmental monitoring, spatial analysis, and Geographic Information System (GIS) technology have improved the ability to characterize pollutant distributions and identify environmental hotspots [15–18]. GIS-based interpolation techniques have been widely applied to visualize pollutant dispersion patterns, assess exposure potential, and support environmental decision-making. Such approaches are particularly useful in rapidly urbanizing regions where comprehensive air-quality monitoring networks are often unavailable.

Despite growing concerns regarding urban air quality in Nigeria, relatively few studies have integrated field measurements of construction-related particulate pollutants with respiratory-health indicators in non-industrial urban environments. Furthermore, available health records are often aggregated at administrative scales that differ from environmental monitoring locations, thereby limiting the ability to establish direct exposure-response relationships. These limitations highlight the need for baseline environmental-health assessments capable of identifying pollutant distribution patterns and informing future investigations.

The present study was therefore designed as a **preliminary ecological assessment** of ambient cement-dust pollution and respiratory-health indicators in Enugu Metropolis, Nigeria. Specifically, the study sought to: (i) quantify concentrations of $PM_{2.5}$, PM_{10}, sulfur dioxide (SO_2), and selected cement-related oxides across twenty-two residential estates; (ii) evaluate their spatial distribution using GIS-based interpolation techniques; (iii) identify potential pollution hotspots associated with construction activities; and (iv) examine available respiratory-health indicators obtained from the Enugu State Ministry of Health within the context of observed environmental conditions. The study does not seek to establish causal relationships between pollutant exposure and disease occurrence. Rather, it provides baseline environmental and health information intended to support future integrated investigations, environmental management strategies, and sustainable urban-planning initiatives in rapidly urbanizing Nigerian cities.

2. Materials and Methods

2.1 Study Area

The study was conducted in Enugu Metropolis, southeastern Nigeria, comprising the urbanized portions of Enugu North, Enugu South, and Enugu East Local Government Areas (LGAs). The metropolis lies approximately between latitudes 6°21′N and 6°30′N and longitudes 7°26′E and 7°37′E. Enugu serves as a major administrative, commercial, educational, and residential center within southeastern Nigeria and has experienced substantial urban expansion over the last two decades.

The climate of the area is tropical, characterized by distinct wet and dry seasons. Annual rainfall ranges from approximately 1,500 mm to 2,000 mm, while average temperatures generally vary between 24°C and 30°C. During the dry season, Harmattan winds originating from the Sahara Desert contribute to elevated atmospheric dust concentrations and influence particulate transport and deposition patterns [17,18].

Although no cement-manufacturing facilities operate within the metropolis, extensive residential, commercial, and infrastructural development activities occur throughout the study area. Cement handling, storage, transportation, and utilization associated with these activities represent potential sources of diffuse particulate emissions [4,5].

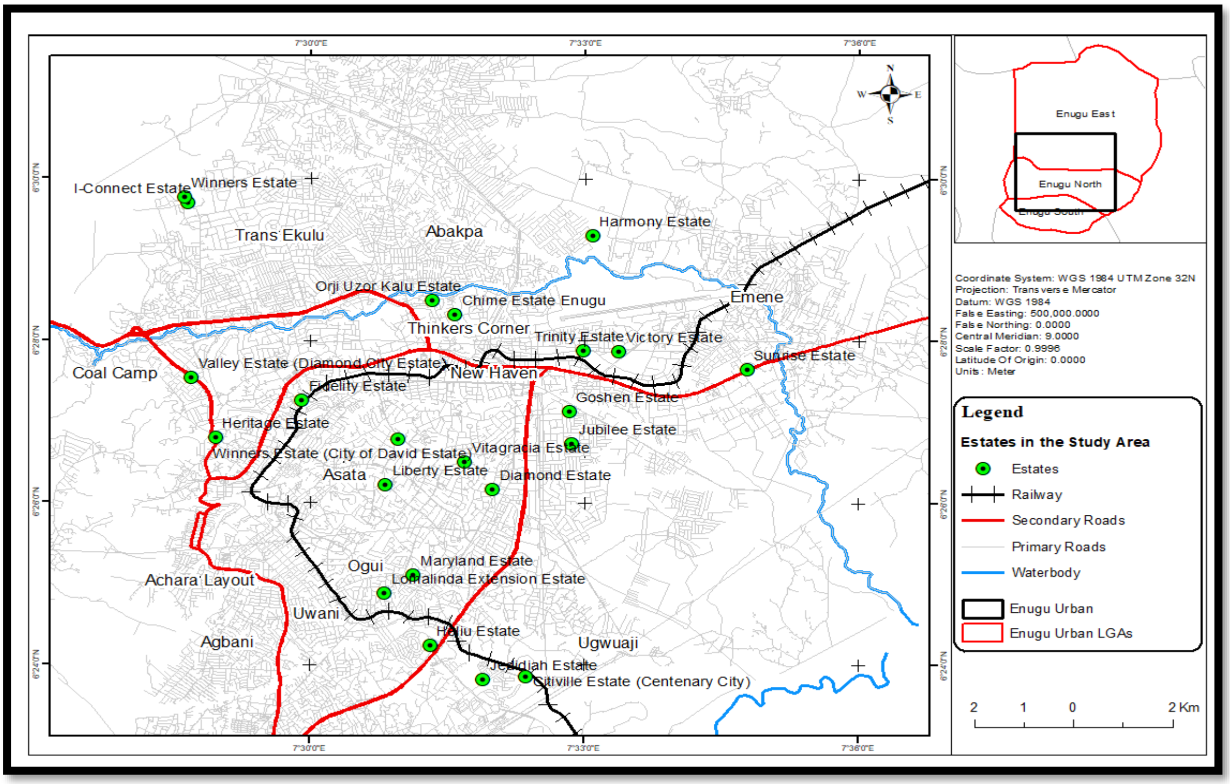

Figure 1. Location of Enugu Metropolis and air-quality monitoring stations.

2.2 Research Design

This investigation was designed as a **preliminary ecological environmental-health assessment**. The study combined ambient air-quality monitoring, laboratory analysis of cement-related particulate constituents, Geographic Information System (GIS)-based spatial analysis, and descriptive assessment of available respiratory-health indicators.

Unlike epidemiological studies designed to establish causal relationships between pollutant exposure and disease occurrence, the present study sought to characterize environmental conditions and examine respiratory-health indicators within the study area. Consequently, findings should be interpreted as exploratory and hypothesis-generating rather than evidence of direct causation [13,14].

2.3 Selection of Sampling Locations

Twenty-two residential estates distributed across Enugu Metropolis were selected for environmental monitoring. The locations were chosen to represent varying levels of construction activity, traffic intensity, population density, and urban development.

Sampling locations included:

1. I-Connect Estate
2. Winners Estate
3. Coal Camp
4. Valley Estate
5. Heritage Estate
6. Fidelity Estate

7. City of David Estate
8. Liberty Estate
9. Orji Uzor Kalu Estate
10. Chime Estate
11. Harmony Estate
12. Trinity Estate
13. Victory Estate
14. Goshen Estate
15. Jubilee Estate
16. Vitagracia Estate
17. Diamond Estate
18. Maryland Estate
19. Lomalinda Extension Estate
20. Heliu Estate
21. Jidejiah Estate
22. Sunrise Estate

Geographic coordinates of all monitoring points were obtained using a handheld Global Positioning System (GPS) receiver and subsequently incorporated into the GIS database.

2.4 Ambient Air-Quality Monitoring

Ambient air-quality measurements were conducted between March and September 2023. This monitoring period encompassed portions of both the dry and wet seasons, thereby capturing seasonal variations in pollutant concentrations.
A **MiniVol Portable Air Sampler** was used to collect particulate samples for determination of $PM_{2.5}$ and PM_{10} concentrations. MiniVol samplers have been widely employed in environmental air-quality investigations because of their portability, reliability, and suitability for field-based particulate monitoring [16,17].
Sulfur dioxide (SO_2) concentrations were measured using a **Bosean Multi-Gas Detector**, which was calibrated according to manufacturer specifications prior to deployment.
Sampling was conducted at approximately breathing height (1.5–2.0 m above ground level) to represent typical human exposure conditions. Care was taken to avoid direct interference from nearby obstacles while maintaining representative site conditions.

2.5 Laboratory Determination of Cement-Related Oxides

Collected particulate samples were analyzed for selected cement-related oxide constituents, including:

- Silicon dioxide (SiO_2)
- Iron oxide (Fe_2O_3)
- Aluminum oxide (Al_2O_3)
- Magnesium oxide (MgO)
- Potassium oxide (K_2O)
- Sodium oxide (Na_2O)

These compounds constitute major components of Portland cement and have been widely used as indicators of cement-related particulate emissions [5,20].
The measured concentrations (See Appendix A1) were compiled for subsequent statistical and spatial analyses.

2.6 Quality Assurance and Quality Control

Quality assurance and quality control (QA/QC) procedures were implemented throughout the study to ensure reliability of field and laboratory measurements.
These procedures included:

- Calibration of monitoring instruments prior to field deployment;
- Standardization of sampling procedures across all locations;
- Verification of field records and sampling logs;
- Validation of laboratory results prior to statistical analysis;
- Cross-checking of coordinate data used in GIS processing.

Meteorological observations recorded during field activities were also considered during interpretation of pollutant distributions.

2.7 Geographic Information System Analysis

Geographic Information System (GIS) analysis was performed using ArcGIS software. GIS-based techniques have been widely applied in environmental assessments for visualization of pollutant distributions and identification of exposure hotspots [15,16].
Coordinates of sampling locations and corresponding pollutant concentrations were imported into ArcGIS to generate spatial distribution maps for:

1. $PM_{2.5}$
2. PM_{10}
3. SO_2
4. SiO_2
5. Fe_2O_3
6. Al_2O_3
7. MgO
8. K_2O
9. Na_2O

Spatial interpolation techniques were employed to estimate pollutant concentrations between sampling locations and produce continuous concentration surfaces across the study area.
The resulting maps were used to identify pollutant hotspots, evaluate spatial patterns, and support interpretation of potential environmental sources.

2.8 Respiratory Health Data

Respiratory-health data were obtained from the Enugu State Ministry of Health. Available records consisted of annual tuberculosis (TB) case reports for Enugu East, Enugu North, and Enugu West Local Government Areas (See Appendix A2)
Tuberculosis data were selected because they represented the most complete respiratory-health dataset available for the study period. However, it should be emphasized that tuberculosis is caused by *Mycobacterium tuberculosis* and is influenced by multiple biological, social, and environmental factors [26].
Because health records were available only at aggregated LGA scales while environmental monitoring was conducted at estate-level locations, direct exposure-response relationships could not be evaluated.

2.9 Statistical Analysis

Descriptive statistical methods were employed to summarize pollutant concentrations measured across the twenty-two monitoring locations. Parameters evaluated included mean, minimum, maximum, and spatial distribution characteristics.

Measured concentrations were compared with applicable air-quality standards established by the World Health Organization (WHO), National Environmental Standards and Regulations Enforcement Agency (NESREA), and Occupational Safety and Health Administration (OSHA) [27,28].

The analytical emphasis of the study was placed on environmental characterization and spatial interpretation rather than epidemiological modeling. Consequently, no causal inference was attempted between measured pollutant concentrations and respiratory-health outcomes.

The results were interpreted within the context of existing literature on particulate pollution, cement-dust exposure, and urban environmental health [1–10,20–25].

3. Results and Discussion

3.1 Overview of Ambient Air Quality Conditions

Ambient air-quality monitoring conducted across twenty-two residential estates revealed measurable concentrations of particulate matter, sulfur dioxide, and several cement-related oxide constituents. The results indicate that construction-related activities, vehicular traffic, and dust resuspension constitute important contributors to ambient pollutant levels within Enugu Metropolis.

The mean $PM_{2.5}$ concentration recorded during the study was 26.59 μg m^{-3}, while the mean PM_{10} concentration was 34.41 μg m^{-3}. These values are comparable to concentrations reported in other rapidly urbanizing Nigerian cities where construction activities and traffic emissions dominate local air-pollution sources [4,17,18]. Although average concentrations generally complied with NESREA and OSHA limits [27,28], localized exceedances of the WHO $PM_{2.5}$ guideline were observed at selected locations, indicating potential environmental-health concerns.

Table 1. Comparison of Measured Particulate Concentrations with Air-Quality Standards

Parameter	Mean Concentration (μg m^{-3})	WHO Guideline	NESREA Standard	OSHA Standard
$PM_{2.5}$	26.59	Exceeds selected guideline values	Within limit	Within limit

Para meter	**Mean Concentration (μg m⁻³)**	**WHO Guideline**	**NESREA Standard**	**OSHA Standard**
PM_{10}	34.41	Within guideline	Within limit	Within limit

The observed concentration levels suggest that although widespread severe pollution was not detected, localized hotspots exist within the metropolis and warrant continued monitoring and management.

3.2 Spatial Distribution of $PM_{2.5}$

The spatial distribution of $PM_{2.5}$ concentrations is presented in **Figure 2**.

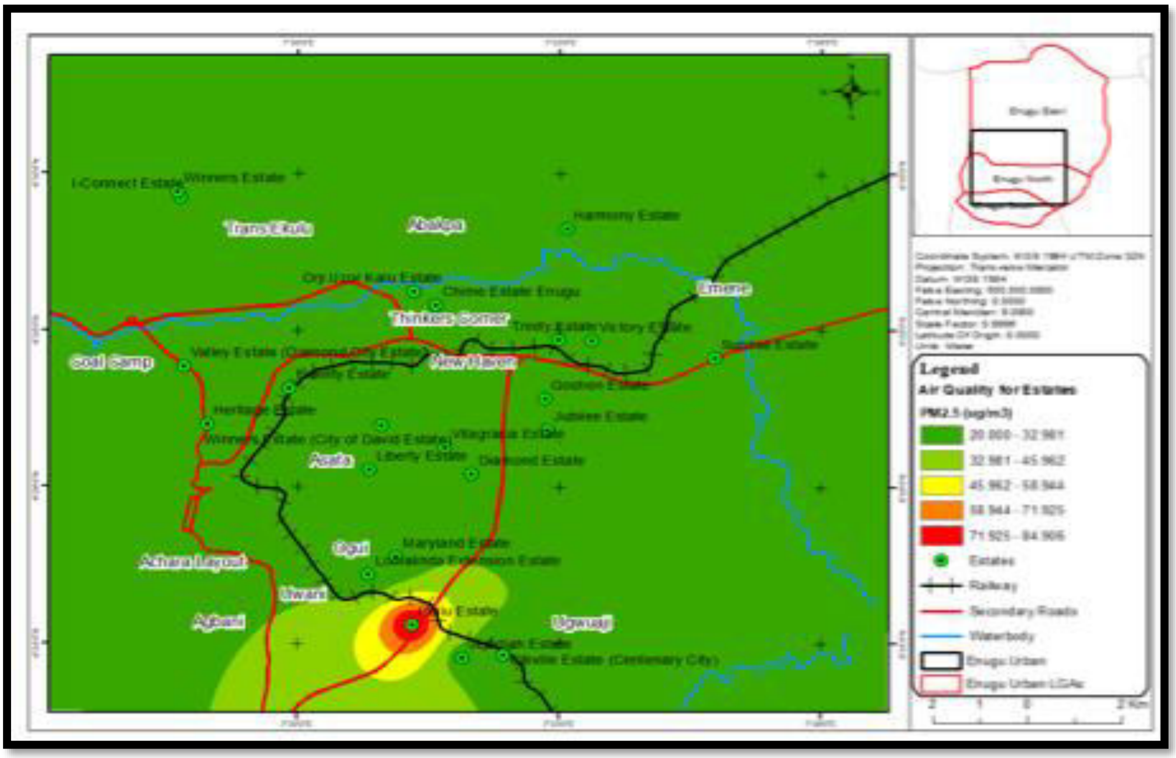

Figure 2. Spatial Distribution of $PM_{2.5}$ Concentrations in Enugu Metropolis.

The $PM_{2.5}$ map reveals a distinct hotspot centered around Heliu Estate and adjoining residential developments in the southeastern portion of the study area. Elevated concentrations were also observed around Goshen Estate, Harmony Estate, and portions of Fidelity Estate.

Fine particulate matter is of particular concern because particles smaller than 2.5 μm can penetrate deeply into the respiratory system and reach the alveolar region of the lungs, where they may contribute to inflammatory responses and respiratory-health effects [1–3]. Similar spatial patterns have been reported in rapidly developing urban environments where construction activities, transportation of building materials, and road-dust resuspension constitute major sources of ambient particulate pollution [15–18].

The concentration gradient observed in Figure 2 suggests that pollutant generation is highly localized rather than uniformly distributed throughout the metropolis. Areas experiencing intensive construction activities appear to correspond with elevated $PM_{2.5}$ levels, supporting observations reported by Ajibade et al. [4] and Adeyemi et al. [17].

3.3 Spatial Distribution of PM_{10}

The spatial distribution of PM_{10} concentrations is presented in **Figure 3**.

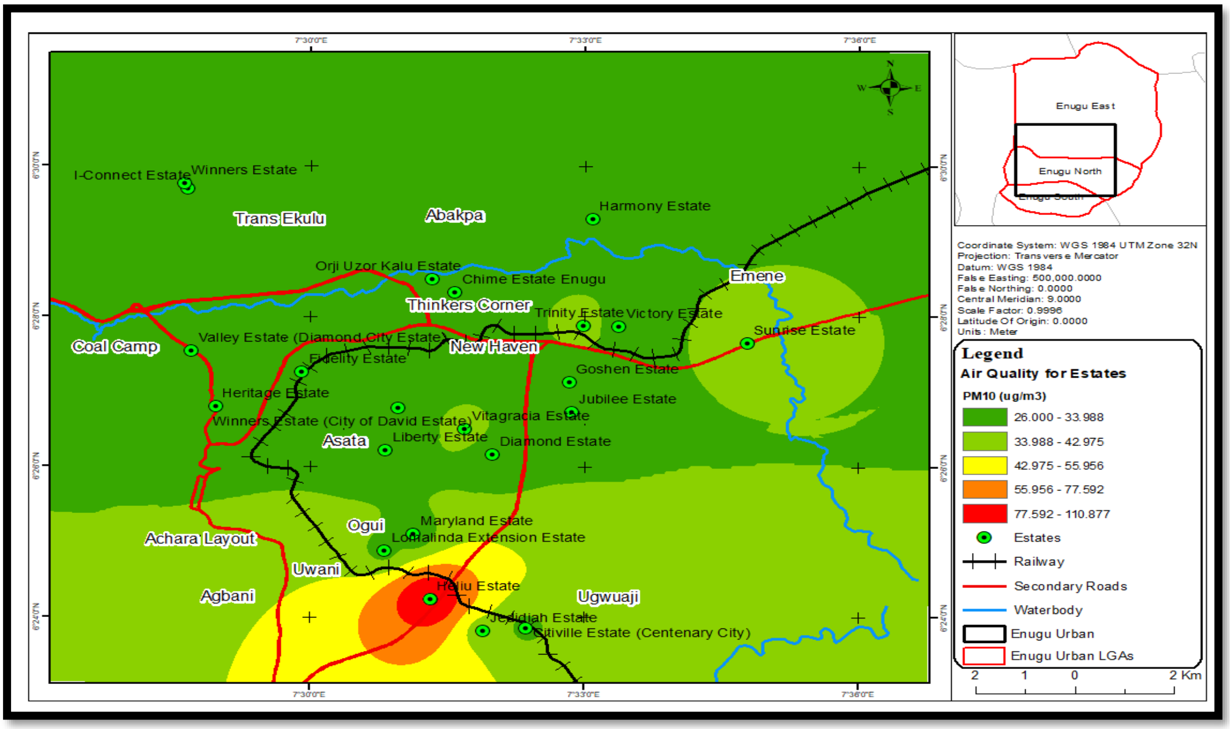

Figure 3. Spatial Distribution of PM_{10} Concentrations in Enugu Metropolis.

The PM_{10} distribution exhibits a pattern generally similar to that of $PM_{2.5}$ but with broader geographic coverage. Elevated concentrations were observed around Heliu Estate and portions of the southern urban corridor.

The broader distribution pattern is expected because larger particulate fractions are generated through mechanical processes such as excavation, material handling, earthworks, and vehicular movement [4,23]. Similar findings have been reported in urban construction environments where coarse particulates are strongly influenced by local development activities [19].

The similarity between $PM_{2.5}$ and PM_{10} distributions suggests that both particle fractions are likely derived from common source mechanisms involving construction-related activities and dust resuspension.

3.4 Spatial Distribution of Sulfur Dioxide (SO_2)

The interpolated sulfur dioxide distribution is presented in **Figure 4**.

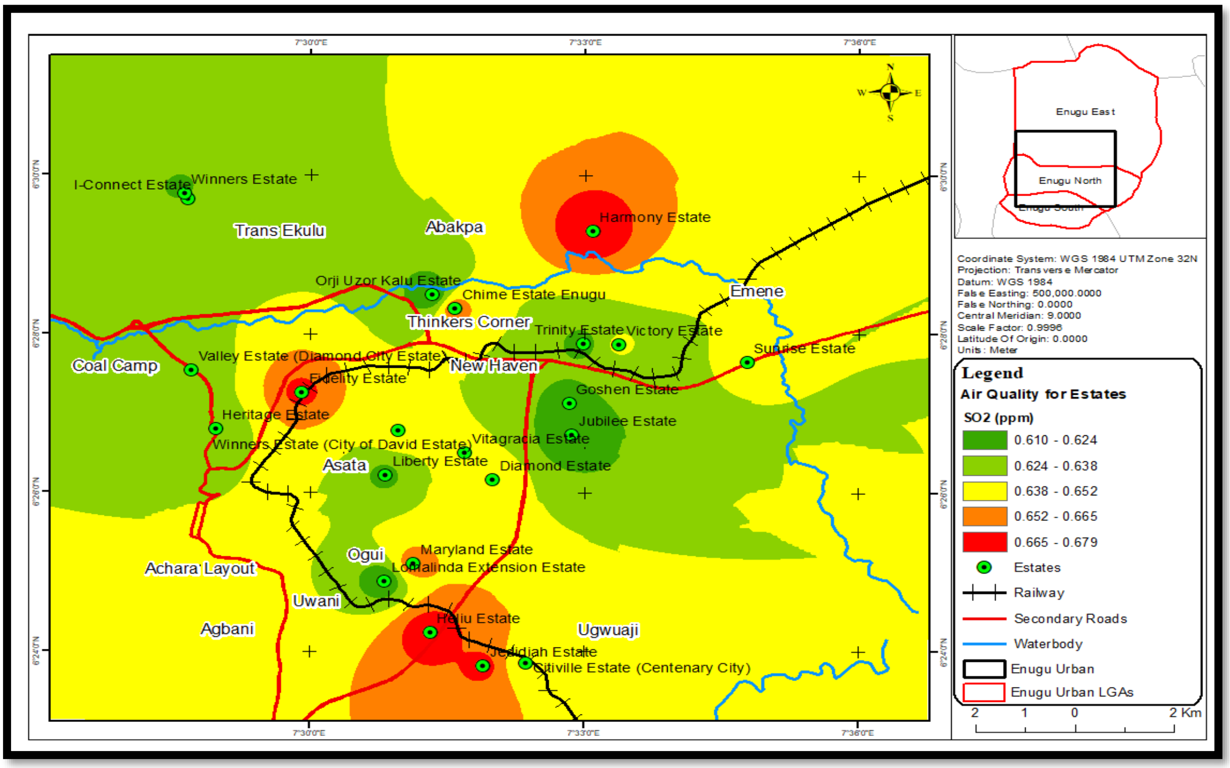

Figure 4. Spatial Distribution of Sulfur Dioxide (SO_2) Concentrations in Enugu Metropolis.

Compared with particulate pollutants, sulfur dioxide exhibited a more dispersed spatial pattern. Localized concentration peaks were observed around Harmony Estate, Fidelity Estate, and Heliu Estate.

Sulfur dioxide is commonly associated with combustion sources, including vehicle exhaust, diesel-powered generators, and fuel-burning activities [14]. Given the absence of major industrial emission sources within the study area, the observed concentrations likely reflect contributions from distributed urban combustion sources rather than large-scale industrial activities.

Overall concentrations remained below levels generally considered hazardous under national and international standards [27,28].

3.5 Spatial Distribution of Cement-Related Oxides

3.5.1 Silica Dust (SiO_2)

The spatial distribution of silica concentrations is shown in **Figure 5**.

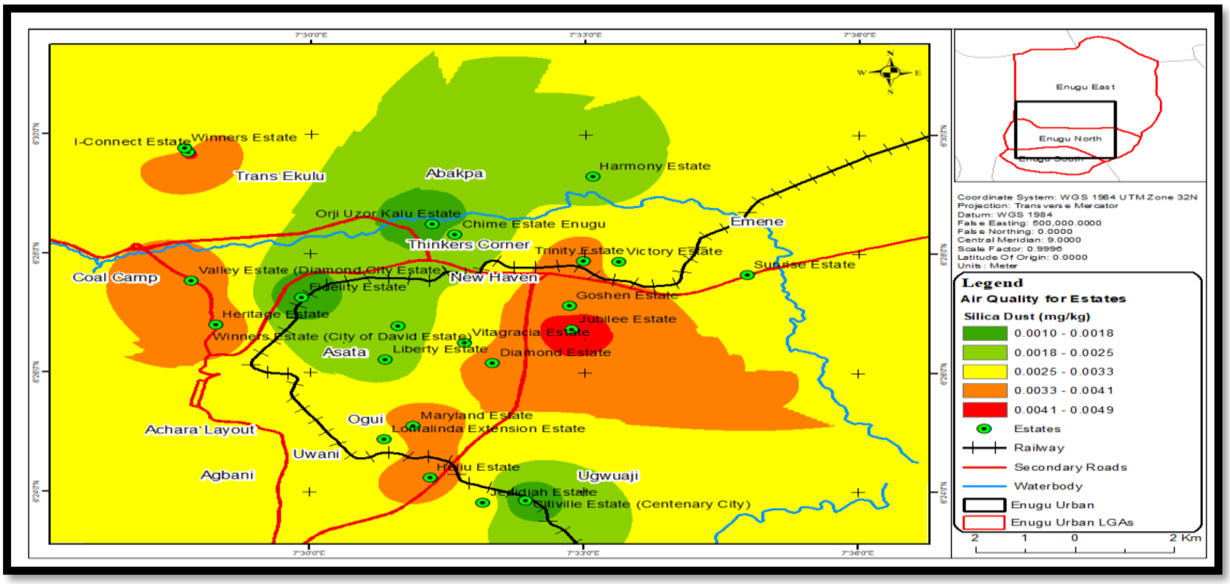

Figure 5. Spatial Distribution of Silica Dust (SiO_2) in Enugu Metropolis.

Silica concentrations were elevated around Jubilee Estate, Goshen Estate, Heliu Estate, and portions of the southeastern study area. Silica represents one of the principal constituents of Portland cement and is frequently used as an indicator of cement-related particulate emissions [5].

The concentration pattern observed in Figure 5 corresponds closely with areas experiencing active construction activities and supports the interpretation that measured pollutants are strongly influenced by building-material handling and associated development activities.

3.5.2 Iron Oxide (Fe_2O_3)

The spatial distribution of iron oxide concentrations is presented in **Figure 6**.

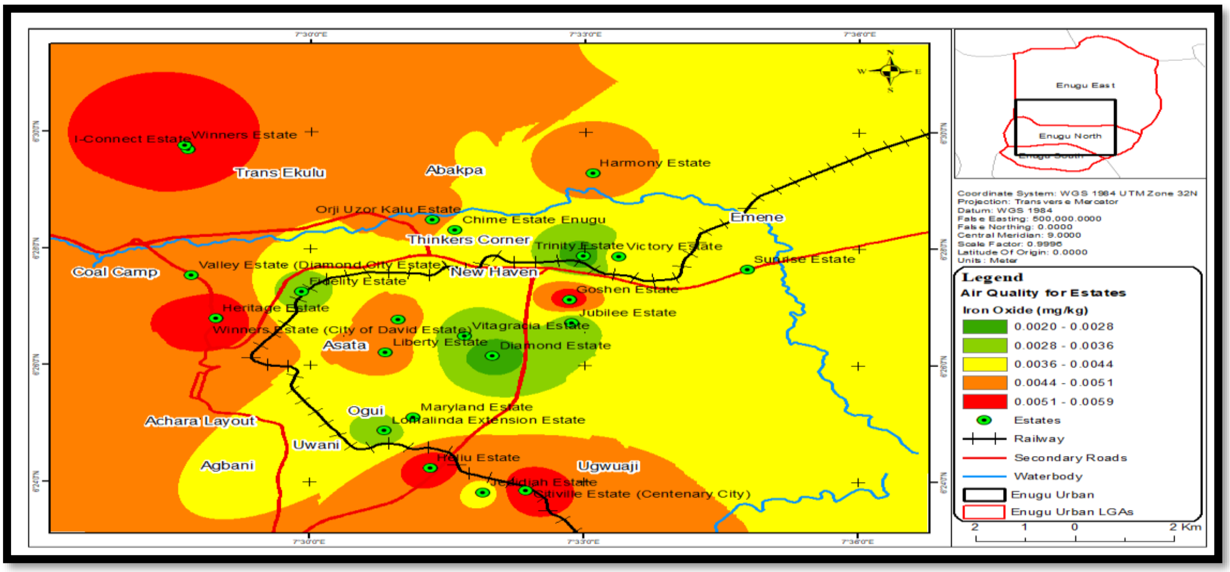

Figure 6. Spatial Distribution of Iron Oxide (Fe_2O_3) in Enugu Metropolis.

Iron oxide concentrations exhibited localized hotspots within both northern and southern portions of the metropolis. Similar findings have been reported in studies of construction-related dust where iron-bearing particulates originate from cement materials, soils, and construction aggregates [20,24].

3.5.3 Aluminum Oxide (Al_2O_3)

The distribution of aluminum oxide concentrations is illustrated in **Figure 7**.

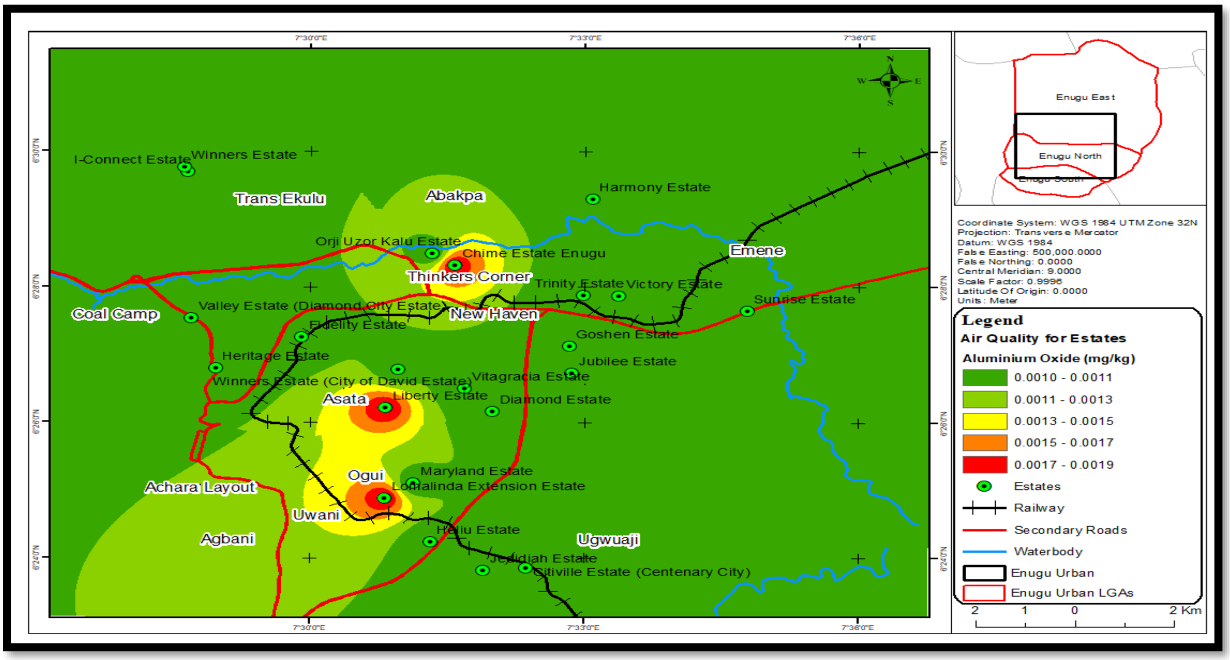

Figure 7. Spatial Distribution of Aluminum Oxide (Al_2O_3) in Enugu Metropolis.

Moderate variability was observed across the study area, with elevated concentrations associated with selected residential developments. Aluminum oxide is a recognized component of cement clinker and contributes to the chemical signature of construction-related particulate emissions [5].

3.5.4 Magnesium Oxide (MgO)

The spatial distribution of magnesium oxide concentrations is shown in **Figure 8**.

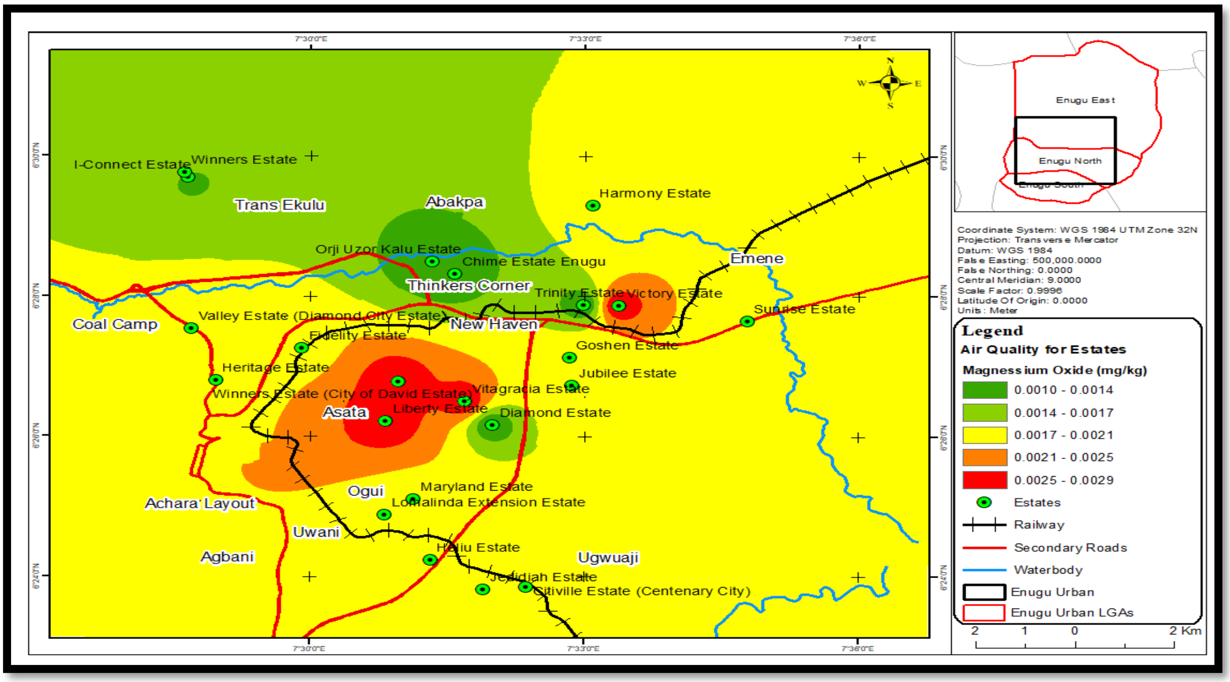

Figure 8. Spatial Distribution of Magnesium Oxide (MgO) in Enugu Metropolis.

Magnesium oxide concentrations remained relatively low throughout much of the study area. Nevertheless, localized concentration peaks were identified within active development zones, indicating contributions from cement-based materials and associated construction operations.

3.5.5 Potassium Oxide (K_2O)

The distribution of potassium oxide concentrations is presented in **Figure 9**.

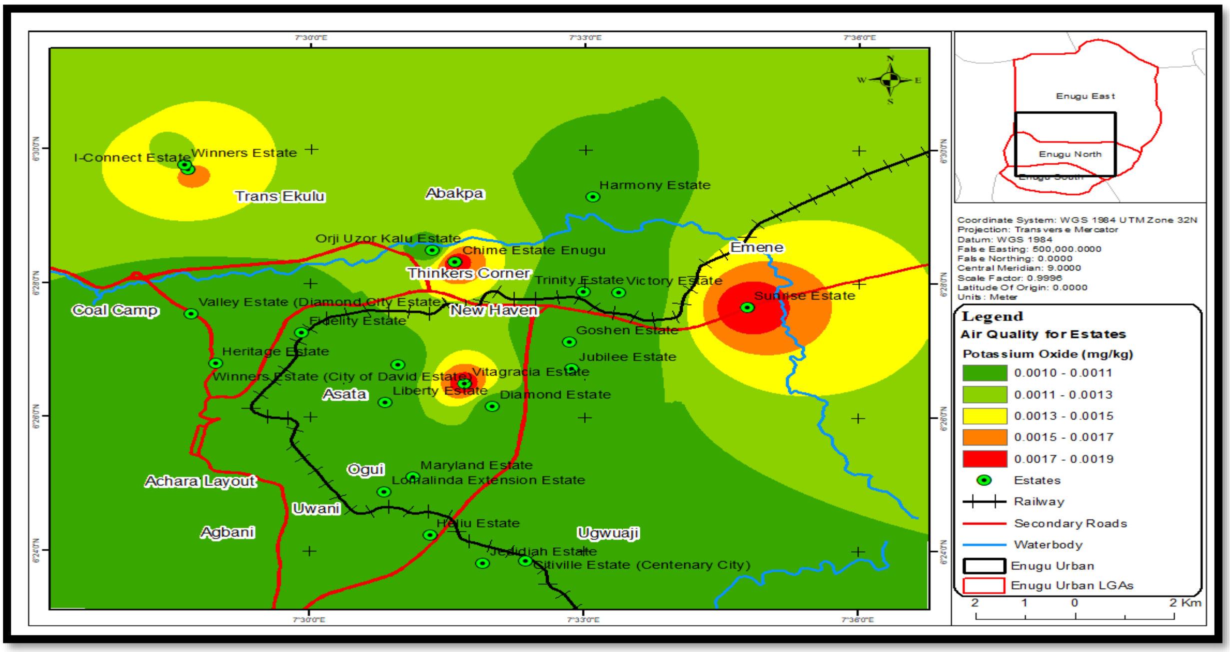

Figure 9. Spatial Distribution of Potassium Oxide (K_2O) in Enugu Metropolis.

Potassium oxide concentrations displayed moderate spatial variation and generally followed patterns observed for other cement-related constituents. The observed distribution further supports the influence of construction activities on local particulate composition.

3.5.6 Sodium Oxide (Na_2O)

The spatial distribution of sodium oxide concentrations is shown in **Figure 10**.

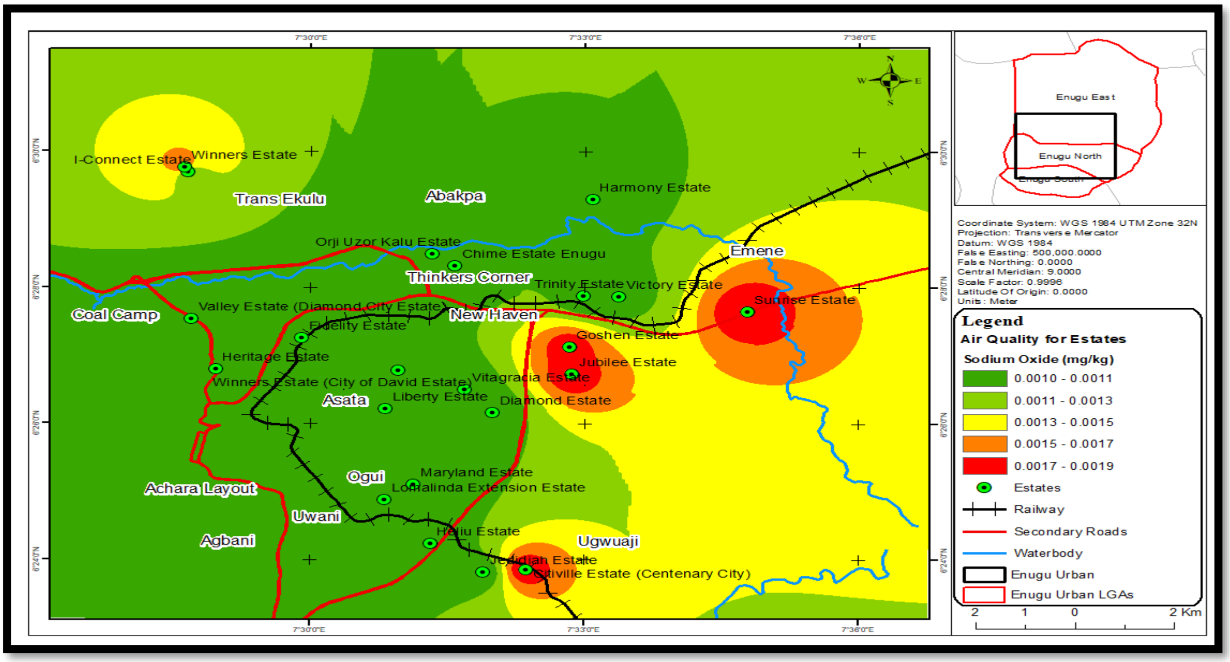

Figure 10. Spatial Distribution of Sodium Oxide (Na_2O) in Enugu Metropolis.

Elevated sodium oxide concentrations were observed around Sunrise Estate and portions of the southeastern study area. Although sodium oxide represents a relatively minor component of Portland cement, its spatial distribution corresponds closely with those of other cement-related oxides.

Collectively, the oxide distribution maps provide strong evidence that ambient particulate pollution within Enugu Metropolis is influenced substantially by construction-related activities rather than by industrial manufacturing sources. The consistency among the various oxide distributions strengthens confidence in the interpretation of construction-related emissions as the dominant source category.

3.6 Respiratory Health Indicators

Tuberculosis data obtained from the Enugu State Ministry of Health indicated a total of 390 reported TB cases within Enugu Urban during 2023.

Table 3. Reported Tuberculosis Cases in Enugu Urban (2023)

Local Government Area	TB Cases
Enugu East	57
Enugu North	74
Enugu West	259
Total	390

Enugu West Local Government Area accounted for approximately 66% of reported cases, indicating the highest disease burden among the three urban LGAs.

Tuberculosis remains a major public-health challenge globally and throughout sub-Saharan Africa [26]. However, tuberculosis is caused by *Mycobacterium tuberculosis* and its occurrence is influenced by numerous biological, social, environmental, and economic factors. Consequently, the available health data should be interpreted as respiratory-health indicators rather than direct outcomes of pollutant exposure.

Because environmental measurements were collected at estate-level locations whereas health records were available only at aggregated LGA scales, direct exposure-response analyses were not possible. This limitation further supports the ecological nature of the present investigation.

3.7 Environmental Health Implications

The results demonstrate that localized hotspots of particulate pollution exist within Enugu Metropolis despite the absence of major industrial emission sources. Construction activities, cement handling, vehicular traffic, and dust resuspension appear to be the dominant contributors to observed pollutant distributions.

Previous studies have demonstrated that prolonged exposure to particulate matter may adversely affect respiratory health by impairing respiratory defense mechanisms and increasing susceptibility to respiratory illnesses [1–3,10]. Nevertheless, the present study was not designed to establish causal relationships between pollutant exposure and respiratory disease occurrence. Instead, the findings provide baseline environmental-health information and identify areas requiring additional investigation.

The GIS-based approach adopted in this study proved effective for identifying pollutant hotspots and visualizing spatial trends. Such information can support environmental management programs, urban planning initiatives, construction-site dust-control measures, and future environmental-health investigations in rapidly urbanizing Nigerian cities.

The study also highlights the importance of developing integrated environmental and public-health databases capable of supporting more sophisticated exposure assessment and epidemiological analyses in the future. Such integrated datasets would facilitate stronger evaluation of potential relationships between urban air pollution and respiratory-health outcomes.

3.8 Comparison with Regulatory Standards

One weakness of the original paper was that it did not sufficiently contextualize the measured pollutant concentrations relative to recognized air-quality standards.

Table 4. Comparison of Measured Particulate Matter Concentrations with Applicable Standards

Parameter	Measured Mean ($\mu g\ m^{-3}$)	WHO Guideline	NESREA Standard	OSHA Standard
$PM_{2.5}$	26.59	15*	Within national limit	Within occupational limit
PM_{10}	34.41	45*	Within national limit	Within occupational limit

*WHO 24-hour guideline values.

The average $PM_{2.5}$ concentration recorded during the study slightly exceeded the WHO 24-hour guideline value but remained below applicable national and occupational standards. In contrast, the average PM_{10} concentration remained within all referenced guideline limits. These findings suggest that although widespread severe particulate pollution was not observed, localized areas may experience elevated exposure levels requiring continued monitoring and management.

The observed results are generally consistent with studies conducted in other rapidly urbanizing cities where construction activities contribute substantially to ambient particulate concentrations [4,17,18].

4. Study Limitations

This study was designed as a preliminary ecological environmental-health assessment and, therefore, possesses several limitations that should be considered when interpreting the findings.

First, the monitoring period extended from March to September 2023 and may not fully capture long-term temporal variations in pollutant concentrations. Air quality is influenced by seasonal meteorological conditions, including rainfall, wind speed, humidity, and atmospheric stability, all of which may affect pollutant transport, dispersion, and deposition patterns. Consequently, the measured concentrations represent conditions during the study period and may not necessarily reflect long-term annual trends.

Second, health data were available only at the Local Government Area (LGA) level, whereas environmental measurements were obtained at individual estate-level locations. This spatial mismatch prevented direct linkage of pollutant exposure to specific disease outcomes and limited the ability to perform detailed exposure-response analyses.

Third, tuberculosis data were used as respiratory-health indicators because of their availability through official public-health records. However, tuberculosis is caused by *Mycobacterium tuberculosis* and develops over extended periods influenced by numerous biological, environmental, and socioeconomic factors. Consequently, the available data do not support causal inference between measured pollutant concentrations and tuberculosis occurrence.

Fourth, several important confounding factors were not available for analysis. These include smoking prevalence, occupational exposure, indoor biomass-fuel use, traffic-related emissions, socioeconomic status, population density, housing conditions, healthcare accessibility, nutritional status, and pre-existing respiratory conditions. Each of these factors may influence respiratory-health outcomes independently of ambient air-quality conditions.

Fifth, although GIS interpolation techniques provide valuable insight into spatial pollutant distributions, the resulting concentration surfaces represent estimates between measured sampling points. Additional monitoring locations would improve interpolation accuracy and provide more detailed characterization of pollutant variability throughout the metropolis.

Notwithstanding these limitations, the study provides valuable baseline information regarding the spatial distribution of construction-related pollutants in Enugu Metropolis and establishes a foundation for future integrated environmental-health investigations involving larger datasets, longer monitoring periods, and more detailed epidemiological information.

5. Conclusions

This study assessed the spatial distribution of cement-dust-related pollutants and examined respiratory-health indicators within Enugu Metropolis, Nigeria. Ambient monitoring conducted across twenty-two residential estates revealed measurable concentrations of $PM_{2.5}$, PM_{10}, sulfur dioxide, and several cement-related oxide constituents, including silica, iron oxide, aluminum oxide, magnesium oxide, potassium oxide, and sodium oxide.

GIS-based spatial analysis identified distinct pollutant hotspots within portions of the metropolis, particularly around Heliu Estate, Harmony Estate, Fidelity Estate, Goshen Estate, Jubilee Estate, and Sunrise Estate. The observed patterns suggest that construction activities, cement handling, traffic emissions, and dust resuspension constitute important contributors to ambient particulate pollution within the study area. Although average pollutant concentrations generally complied with NESREA and OSHA standards, localized exceedances of WHO $PM_{2.5}$ guideline values indicate areas where additional environmental management measures may be warranted.

The spatial distributions of silica, iron oxide, aluminum oxide, magnesium oxide, potassium oxide, and sodium oxide further support the interpretation that construction-related activities represent significant sources of particulate emissions in Enugu Metropolis. These findings demonstrate the usefulness of GIS techniques for identifying pollution hotspots and visualizing environmental conditions in rapidly urbanizing cities.

Respiratory-health data obtained from the Enugu State Ministry of Health indicated a substantial burden of tuberculosis within Enugu Urban during the study period, with the highest number of reported cases occurring in Enugu West Local Government Area. However, because health and environmental datasets were available at different spatial scales, direct exposure-response relationships could not be established. Consequently, the study was intentionally framed as a preliminary ecological assessment rather than a causal epidemiological investigation.

Overall, the findings provide important baseline information for environmental management and urban planning within Enugu Metropolis. The study highlights the need for continuous air-quality monitoring, improved dust-control practices at construction sites, enhanced environmental regulatory enforcement, and development of integrated environmental-health databases. Future investigations should incorporate longer-term monitoring programs, meteorological analyses, larger environmental datasets, and finer-scale health information to better evaluate potential relationships between urban air pollution and respiratory-health outcomes.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Access to health records obtained from the Enugu State Ministry of Health may be subject to applicable institutional and governmental restrictions.

Author Contributions

Chidubem Joseph Okonkwo contributed to field data collection, environmental monitoring, GIS analysis, and manuscript preparation.

Michael Okwudili Egbebike conceived the study, supervised the research, contributed to manuscript preparation and data interpretation, and revised the manuscript.

Charles Obinwanne Okoye contributed to environmental analysis, interpretation of results, and manuscript review.

Anene Nwabu Moneke provided guidance on environmental-health interpretation, study design, and manuscript revision.

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Appendix:

Table A1: Air Quality Samples for Estates

SN	Name	PM_{10}	$PM_{2.5}$	CO_2	SO_2	Silica Dust	Aluminum Oxide	Potassium Oxide	Iron Oxide	Magnesium Oxide	Sodium Oxide
1	I-Connect Estate	30	23	447	0.63	0.005	0.001	0.002	0.005	0.001	0.001
2	Valley Estate, Diamond City Estate	26	20	410	0.63	0.004	0.001	0.001	0.005	0.002	0.001
3	Jubilee Estate	30	23	457	0.61	0.005	0.001	0.001	0.003	0.002	0.002
4	Winners Estate. Legacy Layout	32	25	454	0.62	0.002	0.001	0.001	0.006	0.002	0.002
5	Citiville Estate, Centenary City, Enugu	32	25	430	0.64	0.001	0.001	0.001	0.006	0.002	0.002
6	Jedidiah Estate	39	30	438	0.67	0.003	0.001	0.001	0.004	0.002	0.001

7	Goshen Estate	27	21	444	0.62	0.004	0.001	0.001	0.006	0.002	0.002
8	Liberty estate	27	21	446	0.62	0.002	0.002	0.001	0.005	0.003	0.001
9	Orji Uzor Kalu, Estate	26	20	540	0.61	0.001	0.001	0.001	0.005	0.001	0.001
10	Winners Estate	27	21	472	0.65	0.002	0.001	0.001	0.005	0.003	0.001
11	Harmony Estate	30	23	452	0.68	0.002	0.001	0.001	0.005	0.002	0.001
12	Maryland Estate	29	23	405	0.66	0.004	0.001	0.001	0.004	0.002	0.001
13	Heliu Estate	111	85	650	0.68	0.004	0.001	0.001	0.006	0.002	0.001
14	Fidelity Estate	26	20	1035	0.67	0.001	0.001	0.001	0.003	0.002	0.001
15	Diamond Estate,	28	22	466	0.65	0.004	0.001	0.001	0.002	0.001	0.001
16	Sunrise Estate	39	30	469	0.64	0.003	0.001	0.002	0.004	0.002	0.002
17	Heritage Estate	31	24	411	0.63	0.004	0.001	0.001	0.006	0.002	0.001
18	Lomalinda Extension Estate	32	25	408	0.61	0.003	0.002	0.001	0.003	0.002	0.001

19	Chime Estate	27	21	441	0.66	0.002	0.002	0.002	0.004	0.001	0.001
20	Vitagracia Estate	39	30	467	0.64	0.003	0.001	0.002	0.003	0.003	0.001
21	Trinity Estate	39	30	416	0.62	0.004	0.001	0.001	0.002	0.001	0.001
22	Victory Estate	30	23	452	0.64	0.003	0.001	0.001	0.004	0.003	0.001

Table A2: Respiratory-health data from the Enugu State Ministry of Health

	2019		2020		2021		2022		2023	
LGA	Pneumonia	Tuberculosis	Pneumonia	Tuberculosis	Pneumonia	Tuberculosis	Pneumonia	Tuberculosis	Pneumonia	Tuberculosis
Enugu East	76	45	N/A	N/A	66	31	89	22	N/A	57
Enugu West	104	57	N/A	N/A	152	68	168	143	N/A	259
Enugu North	92	62	N/A	N/A	109	46	124	85	N/A	74
Enugu Urban	**272**	**164**	**N/A**	**N/A**	**327**	**145**	**381**	**250**	N/A	**390**