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Research article

Air Quality in Nigerian Urban Environments: A Comprehensive Assessment of Gaseous Pollutants and Particle Concentrations

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Abstract

Keywords

air quality;
pollution;
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colocation;
Anambra State;
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The rise in gaseous pollutants and particulate concentrations is a serious problem for the environment. This study examined the air quality within four urban areas (Awka, Ekwulobia, Nnewi, and Onitsha) in Anambra State, Nigeria. The concentrations of known air pollutants including suspended particulate matter (PM2.5 and PM10), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), methane (CH_4), volatile organic compounds (VOCs), hydrogen sulfide (H_2S), ammonia (NH_3), ozone (O_3), carbon dioxide (CO_2) and carbon monoxide (CO) were assessed at various locations within the study areas using Aeroqual air quality monitoring devices, and the results were compared with the WHO air quality guidelines for health impact assessment. The air quality index (AQI) was interpolated from the pollutant concentrations in order to show hazard categories of air quality conditions over the study locations. The mean concentrations of SO_2, CH_4, and VOCs within the residential locations of Awka, Ekwulobia, and Nnewi were in the range of 200-8000 µg m^{-3} and exceeded WHO limits for air quality. While the levels of CO_2, SO_2, and CH_4 (3.25-1,027,000 µg m^{-3}) within the commercial locations of Awka, Ekwulobia, and Nnewi exceeded WHO limits, only VOCs (500-1100 µg m^{-3}) within Awka and Ekwulobia exceeded the limits. The 62-181 µg m^{-3} and 40-295 µg m^{-3} ranges of PM2.5 and PM10, respectively within the Nnewi and Ekwulobia commercial locations were the only particle concentrations at which the World Health Organization (WHO) recommended limits for health aspects of air pollution were exceeded. The AQI calculations showed air quality within some of the locations may have potential risks for public health.

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1. Introduction

Air pollution has emerged as one of the most debated phenomena and environmental problems globally. The potential impact of air pollution on climate and atmospheric environment, is shaping environmental geopolitics and influencing key research and industry policies [1-5]. A body of evidence has demonstrated that the quality of air over a place is a function of the activities operating within its confinement, which reflects the extent to which human actions impact the atmospheric environment [6-9].

Some gases such as volatile organic compounds (VOCs; from certain solids or liquids that produce undesirable effects in the atmosphere), oxides of carbon, nitrogen, and sulfur, and particulate matter (PM; a mixture of solid particles and liquid droplets found in the air such as smoke, dust, fumes, aerosols) are present in an amount that can compromise air quality with corresponding adverse effects (respiratory and cardiovascular diseases) on public health [10, 11]. Besides, it is estimated globally that over seven million people die annually due to air pollution-related illnesses [12]. Increases in environmental urban air pollution and associated public health effects have been linked to population growth and artificial environmental pressures resulting from increased population density that stems from mass rural-urban migration, uncoordinated spatiotemporal development clusters, unpredictable consumer behavior, and consumerism, heavy reliance on fossil fuel-based operations, and weak environmental regulations [12-15]. The cumulative risk of air pollution in residential and commercial areas, where potential exposure is high, is increasing, and has led to a widespread ecosystem service disruption at both local and regional levels [16-21].

Air quality monitoring is crucial in assessing the extent of population exposure to air pollutants. Exposure and resulting public health effects appear to vary and depend mainly on the type of pollutant, its severity, period and frequency of exposure, and pollutant toxicity [7, 22-25]. However, the air quality index (AQI) has increasingly become an indicator tool widely used for assessing and indexing the state of an air environment over a place or a region [26, 27]. The range of index values derived from AQI can indicate air pollution and hot spots, and can assist to guide further response actions for quality restoration and/or regulatory approaches [28-30].

While AQI is commonly used in most developed countries and available on accessible digital platforms to guide routine and daily activities of the resident population, this is not the case for some developing countries, including Nigeria, where air quality monitoring is rarely evaluated. For example, Anambra State has no air quality monitoring stations, and data on air quality assessment is scarce despite being one of the key economic hubs in Nigeria. Therefore, critical studies of air quality in key urban centers with rapid development potential in the state are significant and urgently needed to provide the required data for the practical modelling of spatial air quality. The objective of this study was to examine for the first-time air quality in key Anambra State urban areas by characterizing the gaseous and particle concentrations in location-specific samples.

2. Materials and Methods

2.1 Study location

The study was conducted in Anambra State, Nigeria (Figure 1). Anambra is the eighth most populated state by number, and the second most populated state by density in Nigeria. It has a population density of 860 square kilometers [11] and an estimated average density of 1500-2000 persons per square kilometer. Over 60% of people in Anambra State live in urban areas,

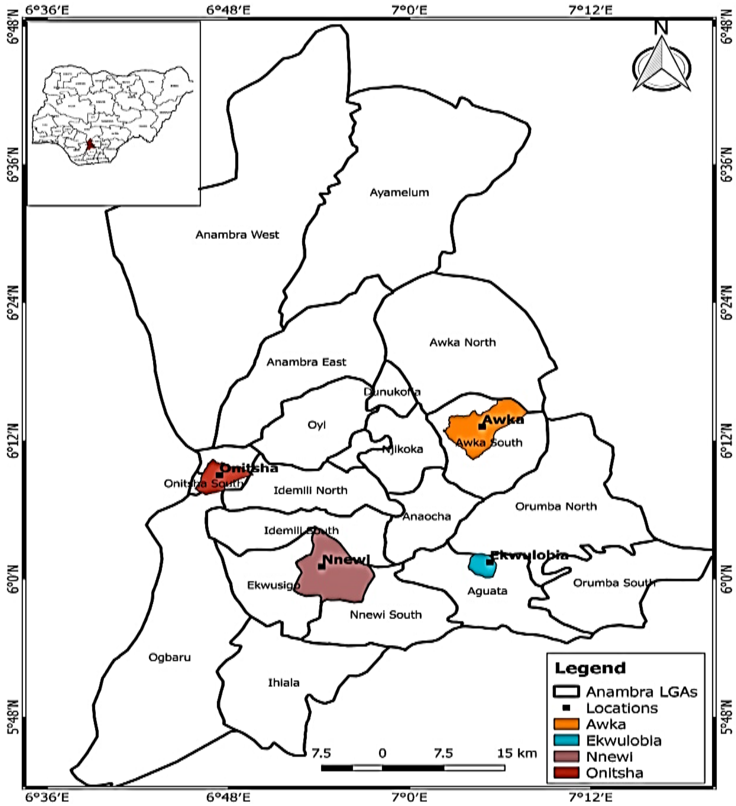

Figure 1. Anambra State Nigeria showing the study locations

making it one of the most urbanized places in Nigeria [31]. The climate is humid tropical with minimum and maximum temperatures of 27ºC and 30ºC, respectively, and a bimodal rainfall peak ranging from 1700-2500 mm annually. Local vegetation in the state, which comprises tropical rainforests, is rapidly disappearing due to unsustainable clearing resulting from development activities.

A comprehensive location analysis was conducted to identify areas in Anambra State with simultaneous residential and commercial urban characters [32]. Awka, Ekwulobia, Nnewi, and Onitsha were selected because they represented the most characteristic locations in Southeastern Nigeria that were consistent with the study requirements (Figure 1). These towns are the largest and most developed urban areas in the state and are characterized by uncoordinated urbanization and industrialization. State government economic programs targeting private sector development have fallen short of providing concurrent safeguard policies to manage environmental risks or mitigate the impact of development. The existing planning policies are inadequate and not systematically designed to set out standard land use zones, and the intended purpose of each zone, which are needed to guide local environmental planning. This inadequacy to address zone appropriacy and needs of local areas at both state and local government levels has resulted in substandard open markets and shopping stalls being indiscriminately located close to critical collector roads, highways, and residential estates. Evidence abounds that such a commercial-residential mix of land use can have substantial environmental effects, an example of which is air pollution [15, 16].

2.2 Monitoring and assessment of air quality

Air quality monitoring stations positioned ~ 25 m from the nearest road were selected according to specific legislation to guarantee the representativeness of the study locations for the measurement of suspended particulate matter (PM10 and PM2.5), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), methane (CH_4), volatile organic compounds (VOCs), hydrogen sulfide (H_2S), ammonia (NH_3), ozone (O_3) and carbon dioxide (CO_2). The Aeroqual commercial sensors used for this study were S500 portable monitors, which are more convenient than the standard sensors normally used. Gas Sensitive Semi-Conductor (GSS) technology, a combination of smart measurement techniques and mixed metal oxide semiconductor sensors that exhibit an electrical resistance change in the presence of a target gas, was used for ozone CO, CO_2, NH_3, CH_4 and VOC_S while Gas Sensitive Electrochemical (GSE) technology, an active sensor technology was used for O_3, NO_2, H_2S and SO_2. Both sensors have an internal fan that pulls air across the gas sensor every 60 s, resulting in a minimum response time of 60 s.

The weatherproof Aeroqual monitors (Series 500) were positioned at ~ 1.5 m elevation above the ground at different focal locations in Awka, Ekwulobia, Nnewi, and Onitsha, and were used to collect air samples for three months (March-May), which covered two seasons (rainy and dry) in the state. Manufacturer's instructions and peer-reviewed studies that validated Aeroqual use and calibration protocols were sequentially followed with slight modifications during the sampling procedure [33]. Aeroqual monitor sensor inlets were positioned in a way that levelled the heads with the lower edge of the weatherproofing to allow sampling of free-flowing ambient air [33]. Monitors were programmed to record a 4-min average concentration of pollutants understudy, and readings were collected weekly through data loggers attached to the devices and downloaded to a computer for analysis.

Quality assurance and quality control (QA/QC) for the Aeroqual instruments were monitored and assessed prior to air quality evaluation (Table 1). Instrument sensors were calibrated against certified analyzers for different air pollutants, with calibrations traceable to national and international standards. The instruments generated 30 continuous readings for each pollutant for 24 h with a high rechargeable battery capacity. The measured levels of pollutants obtained were compared with WHO air quality limits in order to assess potential public health risks posed by detected levels [25]. The measured levels of all pollutants were subsequently transformed into interim AQI using the US EPA AQI derivation model to reflect the implications for public health risk assessment and underpin our observations from WHO air quality comparison. The interim nature of the AQI is such that it becomes iterative and undergoes continuous refining as data availability grows.

2.3 Data analysis

Simple summary statistics including the mean and standard deviation of the data obtained from different stations were conducted using Statistical Product and Service Solutions (SPSS) version 22. The AQI was calculated using 2760 readings for each of the pollutants examined. The AQI values of the pollutant concentrations were calculated using equation (1), which is recommended by the US EPA [34]:

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{HI} - BP_{Lo}} (C_p - BP_{Lo}) + I_{Lo} \quad (1)$$

Where I_p = the index for pollution p
C_p = the truncated concentration of pollutant p
BP_{Hi} = the concentration breakpoint that is $\geq C_p$
BP_{Lo} = the concentration breakpoint that is $\leq C_p$
I_{Hi} = the AQI value corresponding to BP_{Hi}
I_{Lo} = the AQI value corresponding to BP_{Lo}
AQI = Max (I_p) (where p=1, 2, 3…n; denotes n pollutants)

Table 1. Calibration of Aeroqual monitors (Series 500, Auckland New Zealand)

Pollutant (µg m^{-3})	Temperature (°C)	Relative humidity (%)	Calibration standard	Mean AQL sensor ± SD (µg m^{-3})
CO_2 (0 – 360002)	25.0	35.0	0.000	0.00±0.000
CO (0 – 28640)	25.0	25.9	0.000	0.00±0.000
SO_2 (0 – 26201)	24.2	42.5	0.000	0.00±0.000
NO_2 (0 – 1882)	27.3	43.3	0.016	19.00±2.000
CH_4 (0 – 656036)	24.5	44.5	0.006	2.00±1.000
NH_3 (0 – 69653)	24.0	45.0	0.000	0.00±0.000
VOC_s (0 – 80728)	24.4	25.3	0.000	0.00±0.000
H_2S (0 – 13939)	24.2	30.8	0.000	0.00±0.000
O_3 (0 – 982)	29.5	33.8	0.009	16.00±2.000
PM2.5 (0 – 1000)	-	-	0.000	0.00±0.000
PM10 (0 – 1000)	-	-	0.000	0.00±0.000

3. Results and Discussion

3.1 Gaseous pollutant and particle concentrations: levels and public health risks

The mean concentrations of pollutants within the residential and commercial areas of Anambra State are presented in Tables 2 and 3. Oxides of carbon (CO_2 and CO) recorded the highest concentrations across towns within both residential and commercial areas. Methane (CH_4) concentrations in all the towns examined, except Onitsha, were elevated and exceeded WHO limits (Tables 2 and 3). Residential areas (Awka, Ekwulobia, and Nnewi) had an SO_2, CH_4, and VOC concentration range (200-800 µg m^{-3}) which exceeded WHO limits (Table 2). While concentrations of CO_2, SO_2, and CH_4 within commercial locations of Awka, Ekwulobia, and Nnewi exceeded those of WHO limits, measurements showed that only the VOC concentrations within Awka and Ekwulobia surpassed the WHO limits (Table 3). The range of PM2.5 and PM 10 (0.01 and 19.75 µg m^{-3}) measured within residential areas were below WHO limits, which was dissimilar to the commercial areas in which PM2.5 and PM 10 within some locations exceeded WHO limits (Tables 2 and 3). For example, concentrations of PM2.5 and PM10 in Ekwulobia and Nnewi, which ranged 62-295 µg $m^{-3,}$ were above the WHO limits and pollutant breakpoints for the health aspect of air pollution (Tables 3 and 4).

The levels of pollutants measured within both residential and commercial areas of Awka, Ekwulobia, Nnewi, and Onitsha was highly variable, which may have resulted from temporal characteristics of the study location geography, type of pollutant and activity, modifying effects of meteorology (e.g., the chemistry of the atmosphere and climate) and the nonlinear integrated global

Table 2. Concentrations of pollutants in residential areas of Anambra State (μg m^{-3})

Pollutant	Awka	Ekwulobia	Nnewi	Onitsha	WHO Limit
CO_2	926500±3.7	92925±5.2	1007000±4.6	1008.5±2.1	630000
CO	17470±4.3	13402.5±1.9	575±6.1	ND	30000
SO_2	280±2.3	740±4.1	415±0.2	1.08±0.1	20
NO_2	ND	35.8±7.6	22.5±6.3	0.03±0.01	200
CH_4	8000±4.2	6000±5.7	510±1.5	20±1.4	160
NH_3	ND	ND	ND	ND	100
VOC_s	250±7.7	200	400	1.6±0.1	100
H_2S	ND	40±8.1	15±7.1	0.05±0.05	100
O_3	ND	ND	ND	ND	100
PM2.5	9±1.4	8.5±1.3	10±1.4	0.01	25
PM10	14±1.4	19.75±4.0	13.5±1.7	0.021±0.02	50

Table 3. Concentrations of pollutants in commercial areas of Anambra State (μg m^{-3})

Pollutant	Awka	Ekwulobia	Nnewi	Onitsha	WHO Limit
CO_2	1092500±1.5	930000±2.4	1027000±9.4	1116.5±3.3	630000
CO	2580.0±8.2	15292.5±1.2	10555±7.8	0.27±0.02	30000
SO_2	290±2.4	160±1.7	32	3.25±0.4	20
NO_2	ND	18±9.6	45±7	0.04	200
CH_4	8000±5.2	12750±1.5	25500±1.3	18±1.4	160
NH_3	ND	ND	ND	ND	100
VOC_s	1100±1.4	500±3.2	50±7.1	0.40±0.14	100
H_2S	ND	245±4.9	330±14.14	0.03±0.01	100
O_3	ND	ND	ND	ND	100
PM2.5	11.5±3.5	62±2.8	181±2.7	0.03±0.01	25
PM10	26.5±9.1	295±6.9	43±4.2	0.041±0.01	50

Table 4. Pollutant breakpoints for PM2.5 and PM10 adapted from Federal Register [54, 75]

Pollutant Breakpoint	24-h PM2.5 (μg m^{-3})	24-h PM10 (μg m^{-3})	Index Category
0 – 50	0-12	0-50	Good
51 – 100	13-55	51-150	Moderate
101 – 200	56-150	151-350	Unhealthy
201 – 300	151-250	351-420	Very unhealthy
301 – 500	251-350	421-500	Hazardous

system model [35-38]. These factors are known to affect outcomes in weather related measurements [36-38]. The elevated levels of oxides of carbon (CO_2 and CO) in areas examined adds to the body of evidence on relative stability of CO_2 and CO as universal constituents of the atmosphere and may have skewed our results [39-41]. It is still difficult globally to predict the contribution of natural sources to urban carbon concentration, particularly for CO_2 [39, 40]. Carbon(ii)oxide is the most abundant air pollutant present in the atmosphere with no known large natural sources and with ~ 60% of emissions into the environment originating from human activities [25, 40]. Therefore, no known source inventory of CO_2 and CO for Anambra State presently exists but the level in some examined locations, despite being below WHO limit, is a source of concern given the potential public health effects of increased oxides of carbon in the air. Both acute and chronic exposure to CO_2 and CO are associated with an increased risk of adverse cardiopulmonary events, and rising trends with public exposure can result in death in the presence or absence of other gaseous pollutants [42, 43].

Both SO_2 and CH_4 within the residential and commercial locations of Awka, Ekwulobia, and Nnewi exceeded those of WHO limits, suggesting that potential health risks from exposure may be detrimental to public health. Approximately 99% of SO_2 and CH_4 in the air are released from human sources and fuel-based mass emissions, including industrial activities and process materials that contain sulfur and methane; for example, electricity generation from coal, oil, or gas [44-47]. Inhalation exposure to a high concentration of these gases can result in adverse health outcomes. Sulfur(iv)oxide contributes to respiratory symptoms in both healthy patients and those with underlying pulmonary diseases [42]. Methane (CH_4) is widely known to disrupt global and regional climate with attendant effects on public health, an example of which is increased mortality in an exposed population [48-50].

Our studies found that VOC concentrations within residential areas (Awka, Ekwulobia, and Nnewi) and commercial areas (Awka and Ekwulobia) exceeded those of WHO limits. These exceedances imply that population exposure could increase the risk of morbidity. Volatile organic compounds are a group of air pollutants emitted from multiple sources of anthropogenic activities (e.g., power and gas stations and fossil fuel-based vehicles) with some species known or suspected to be carcinogenic and may affect the immune system, brain, liver, and kidneys [51-53].

The concentrations of PM2.5 and PM10 within commercial areas (Ekwulobia and Nnewi), that surpassed WHO limits and are regarded as unhealthy following the pollutant breakpoints recommendations by the Federal Registry [54, 75], for particulate matter and fine particulate matter (Table 4). These potentially pose a threat to the environmental health of those localities in light of the concentrations examined and higher devastating health effects known to be associated with particulate pollution than other air contaminants. Gaseous pollutants examined in this study, while potentially harmful to health, may have adverse health outcomes with a lower threshold than particulate matters [54], an observation which is consistent with a suite of clinical studies. Multiple studies have demonstrated the correlation between particulate matter in the air and increased morbidity and mortality through, for example, relative risks of cardiorespiratory mortality [55] and cardiovascular-metabolic diseases and endocrine disruption [56-58]. This calls for the regulatory authorities to devise a mechanism to combat accelerated particulate emissions to the environment. Akinfolarin *et al*. [59] reported elevated levels of total particulate matters that exceeded standards in Port Harcourt's oil and gas commercial centers, and suggested that the use of fossil fuels and industrial clusters appeared to contribute to quality degradation of the air.

3.2 Air quality index

The results of AQI data derived for residential and commercial areas in Anambra State are presented in Tables 5 and 6, respectively. The levels of health concern observed with the comparison of our AQI values to those of US EPA, particularly values above 100 (AQI > 100) (Tables 5-7), are concerning with regard to health exposure outcomes, including sensitive population groups (e.g., asthmatics, children and elderly, people with heart or lung diseases) and groups who spend long hours exposed to the air [60-64]. The deteriorating conditions of air quality within the study areas may stem from random development clusters (e.g., markets and business centers around residential areas) and the heavy reliance of domestic activities on fossil-based fuels (e.g., cooking and vehicular). During reconnaissance tour and feasibility analysis, we observed the disorderly colocations of commercial activities and residential living within the study areas. Anambra State has since 2003 commenced decentralization and geographic clustering of similar product-markets in one place to reduce overcrowding within the existing business premises across the state. The approach, however, is unsystematically planned to enable the sustainability of other dependent urban functions and contain spillovers. The strategic implication of this uncoordinated development is that air quality will continue to deteriorate until Anambra State realigns land-use zoning priorities and balances economic development and the environment with appropriate sustainable regulatory instruments [6, 65, 66]. Our results are not an isolated incident, as similar outcomes have been reported elsewhere in Southeastern Nigeria. One study, for example, found that air quality over a residential area in Enugu, which is approximately 90 km from Anambra State, was highly polluted apparently from petroleum-based combustion [67]. The study further demonstrated that commercial areas clustered around the residential area had higher concentrations of CO, CO_2, CH_4, SO_2, NO_2, PM2.5, PM10 and may have contributed to the pollution in the residential area.

Table 5. Air Quality Index values of pollutants in residential areas of Anambra State

Pollutant	Awka	Ekwulobia	Nnewi	Onitsha
CO	104	57	98	0
SO_2	0	323	138	0
NO_2	0	72	10	0
O_3	0	0	0	1
PM2.5	38	35	42	0
PM10	13	18	12	0

Table 6. Air Quality Index values of pollutants in commercial areas of Anambra State

Pollutant	Awka	Ekwulobia	Nnewi	Onitsha
CO	16	64	13	2
SO_2	0	130	46	0
NO_2	0	8	47	0
O_3	0	0	0	4
PM2.5	48	154	231	0
PM10	81	171	40	0

Table 7. Air Quality Index and its levels of health concern adapted from US EPA [34]

AQI values (↓)	Levels of health concern (↓)
0 – 50	Good
51 – 100	Moderate
101 – 150	Unhealthy for sensitive groups
151 – 200	Unhealthy
201 – 300	Very unhealthy
301 – 500	Hazardous

3.3 Environmental land use planning is the key to sustainable development in Anambra State

Development must assist, rather than hinder, reduction in environmental issues. Urban development is a critical environmental issue, as development influences the levels of contaminant emissions associated with buildings, infrastructure expansion, industrial processes, transport, and energy supply systems [7, 66, 68, 69]. If Anambra State is to reduce emissions into its environment and improve air quality, the urban system must be a crucial component of 'whole of government' integrated responses to development strategies. We provide in Figure 2 an integrated conceptual model that encompasses various elements of local environmental land use planning to underpin development policies and approaches in Anambra State. Effective urban development planning strategies must include factors such as spatial zoning and land use prioritization, sensitive clustering, strategic development appraisal, public transport networks, and road infrastructure, all coordinated in a systematic process. These aspects must be handled proactively and managed by institutional arrangement and practices under exclusive state-sensitive planning policies enacted through an adequate community of practice and public consultation process that takes onboard community demands and aspirations while balancing the economic, environmental, and social components.

Given that the population of Anambra has been projected to increase at a growth rate of 2.21% per annum above the 2016 population of 5,527,809 people [31], it is anticipated that components of the urban system — e.g., physical infrastructure and energy systems — will surge resulting in significantly increased population pressure in inner suburbs and traffic densities. Anambra State must develop planning policy guidance for town and retail development consistent with its environmental character. The current unregulated and unplanned colocation of commercial retails, and residential estates appears not to be working, rather it seems to be worsening the current environmental crisis. A preferred urban form that is suitable for Anambra State from the perspective of air quality and mixed land use–is yet to be determined from available evidence. There is a significant information gap that needs to be investigated and understood in order to further manage existing and emerging environmental air quality issues within the region. We, however, reiterate our recommendation that appropriately modeled integrated road and transport infrastructure and environmental land use planning are important long-term strategies for regulating Anambra State development and reducing pollution. Both existing and future development, including the design and location of physical infrastructure, must consider the potential environmental risks and develop suitable mitigation and safeguard policies to manage those risks. Environmental impact assessment (EIA), which is a risk prevention tool mostly applied to significant projects in many countries, is still not rigorously applied in Anambra State despite the existence of the legislative framework at the national level [70-74]. While we additionally recommend that EIA becomes the hallmark of any development project proposals in Anambra State, a range of policies including urban planning, building control, codes of practice, and standards must underpin any national, regional, and local development plans. Since there is a strong connection between health risks and proximity of air pollution sources, local jurisdictions are more positioned to manage local environmental planning and be responsible for determining land use compatibility. The suggested goal, objectives, and policies strategies related to land use for local environmental planning in Anambra State must evolve by first mapping and taking inventory of sources of air pollution, and by identifying sensitive locations and receptors for priority and special purpose zoning that ensure protection of environmental layers.

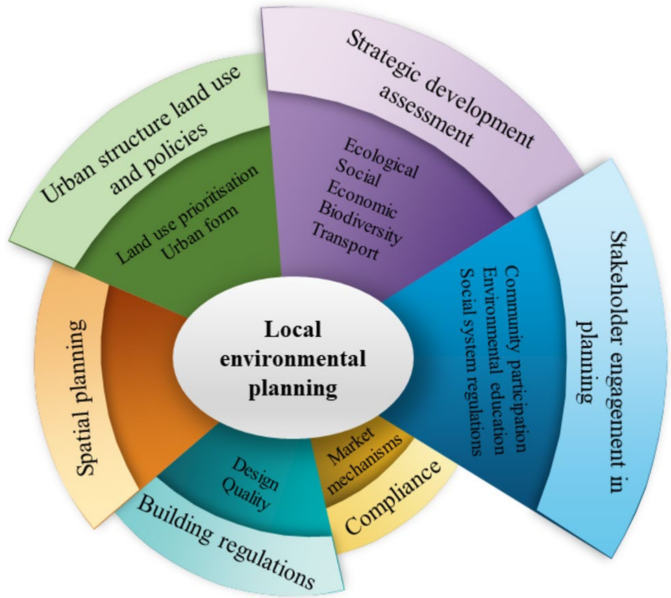

Figure 2. Conceptual model for local environmental land use planning in Anambra State, Nigeria

4. Conclusions

The study has demonstrated the extent of air pollution in Anambra State and the potential risk it portends to public health, notwithstanding the contextual limitations associated with the inter-country and continental adoption of air quality indexing. The exceedances of WHO air quality guidelines for health impact assessment by pollutant concentrations within residential and commercial areas of Anambra State indicate that both land uses have effects on the spatial pollution observed and underscore the need for Anambra State to initiate a monitoring program aimed at taking an accurate inventory of pollutant concentrations in air for robust environmental health planning and region-specific development of AQI. This study will facilitate the land-use planning principles of the state, including consideration of evaluating impact on air quality as part of the local environmental planning process, and improved air quality as a result of integrating these principles. The study can help planners and developers understand how their decisions influence air quality and map out ways by which harmful effects can be reduced or avoided. Additionally, development within the state must be effectively coordinated and underpinned by land-use planning policies that balance environmental, economic, and social performance outcomes.

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