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Indoor Air Pollution by $PM_{2.5}$ and PM_{10} and their Potential Health Burden in Low, Middle and High-Income Residential Areas of Enugu Metropolis, Enugu State, Nigeria

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Household sources of air pollution play a major role in determining the overall quality of life. Air pollution has been reported to greatly affect public health and contributes significantly to respiratory and cardiovascular disease prevalence. In this study, the concentration values of indoor $PM_{2.5}$ and PM_{10} were measured in different residential areas (Independence layout, New Haven layout and Ogui New layout) of Enugu Metropolis covering dry and wet seasons using Bosean K-600M portable multi-gas detector. The health burden across the three residential areas was determined using AirQ+ modeling software. In comparison with the middle- and low-income areas, the higher-income residential area (Independence layout) did not have significantly lower levels of $PM_{2.5}$ in the dry season but did in the wet season. About 10 people are likely to suffer chronic obstructive pulmonary disease (COPD) in Independence layout whereas for the middle- and low-income areas (New Haven and Ogui New layout) about 15 people will suffer COPD. Furthermore, 5 and 16 people are likely to suffer from ischemic heart disease (IHD) and acute lower respiratory infections (ALRI) respectively in Independence layout whereas for Ogui New layout and New Haven, 6 and 20 people will suffer IHD and ALRI, respectively. These numbers are worrisome and justify the urgent formulation and implementation of measures by the government to reduce airborne particulate matter in the study area.

Keywords: Indoor air pollution, Household air pollution, Particulate matter, Burden of disease.

INTRODUCTION

Air pollution occurs when there are chemical, biological or physical contaminants in the atmospheric environment around us, causing an alteration in the indoor or outdoor atmosphere [1]. The presence of these harmful contaminants in excessive or even minute amounts over prolonged periods, can cause harm to human health and the environment [2]. The air pollutants of concern are particulate matter with aerodynamic diameter 2.5 and 10 microns. Sources of air pollutants include transportation, industries, agricultural practices and household sources. Within households, air pollution can be introduced from cooking, lighting or heating activities. Particulate matter is of particular concern since it is released from the use of these fuels as well as human activities, into the indoor air environment. These fine particles compromise the air quality and potentially affect the health and body systems of the residents.

According to the WHO, 2024 [3], air pollution has been declared to be a significant environmental risk threatening human health and claims the lives of an estimated 6.7 million individuals each year. Attributable death due to air pollution from household sources was estimated to be 2.31 million in 2019 [1]. The number has risen to 8.1 million in 2021 and 38% of these death cases is from household air pollution [4]. Household air pollution leads to non-communicable diseases such as chronic obstructive pulmonary disease, ischemic heart disease and lung cancer as well as acute lower respiratory infection [5]. While outdoor and indoor air pollution contribute to this burden, indoor air pollution, especially exposure due to particulate matter (PM) is of critical concern in many regions [6]. This is particularly important in developing countries where access to clean energy sources is grossly inadequate [2,7]. Furthermore, the air quality in household indoor spaces can also be affected by other factors such as behavioural factors such as smoking, use of insecticides, pesticides, candles and paint and building characteristics like the ventilation conditions and crowding [8-10].

It is estimated that in Nigeria, the age-standardised mortality rate attributed to household and ambient air pollution was 165.2 per 100,000 population with only 22% of the population with primary reliance on clean fuels and technology in 2022 [11]. Residents of Enugu state of Nigeria are facing a complex challenge with regards to indoor air pollution. While the majority of vehicles are still powered by petrol and diesel engine, household generators that augment power supply are powered by these unclean fuels too. The available options for cooking fuels are wood, charcoal, kerosene and the cleaner fuel which is gas. The high cost of gas though cleaner makes it an unpopular energy source for cooking fuel.

Among the continents of the world, Africa is the poorest. At the same time, Africa is on the path of a development trajectory that needs to be balanced with environmental stewardship to engender sustainable development. The United Nations Sustainable Development Goals (SDGs) recognised the interconnection between economic, social and environmental aspects of human wellbeing and aims to address some of the inequalities to promote sustainable development [12]. Monitoring air pollution is intrinsically connected to multiple Sustainable Development Goals (SDGs), including SDG 3 (Good Health and Well-Being) by reducing pollution-related health risks, SDG 7 (Affordable and Clean Energy) through the promotion of cleaner energy sources, SDG 11 (Sustainable Cities and Communities) by supporting healthier urban environments and SDG 13 (Climate Action) through the control of air pollutants that contribute to climate change. Reducing death and illness due to air pollution, ensuring households have access to clean energy and reducing the environmental impact of air pollutants work towards fulfilling these goals. By doing these, one can achieve cleaner air for everyone, improve human health and contribute positively to environmental wellness

The WHO also relies on the satellite data, ground measurement from reference-grade monitoring stations as well as atmospheric chemical transport models of particulate matter and research data of household air pollution to calculate the burden of disease attributable to air pollution [13,14]. Several reviews on air quality and respiratory health in children have been able to show evidence that indoor air pollutants have a wide range of adverse effects including an increased risk of acute lower respiratory infections in children which is a leading cause of under-5 mortality [15-17]. Indoor air pollution (IAP) also increases the incidence of COPD and is associated with low birth weight, increase infant and prenatal deaths, as well as diseases such as cataract, tuberculosis, laryngeal, nasopharyngeal and lung cancers [18]. Many studies have established links between air pollution and premature deaths of old and sick, respiratory diseases, brain ailments, prenatal mortality, low birth-weight and cardiac diseases [19-21].

Another study on the baseline population asthma rates estimated that about 1.85 million new pediatric asthma cases were attributable to NO_2 pollution globally [22]. Almost 90% of urban inhabitants reside in areas that exceeded WHOs air pollution guidelines for the yearly average of 5 $\mu g/m^3$ for $PM_{2.5}$ [18,23]. This deviation from the recommended annual value resulted in an excess of 1.8 million attributable deaths in 2019. The financial strain and loss in productivity due to air pollution related issues cannot be over emphasised. Healthcare expenditure on drugs and antibiotics, hospital visits and admissions were significantly increased due to the burden of respiratory diseases [24].

Despite these risks, there is a notable paucity of measured indoor air quality data in South-Eastern Nigeria. Most existing studies in the region focus on outdoor ambient air, leaving a critical knowledge gap regarding how indoor PM exposure varies across different socio-economic residential layouts. Furthermore, the quantitative health burden of these exposures is yet to be modeled locally using standard epidemiological tools. This study addresses these gaps by providing the first comprehensive assessment of indoor $PM_{2.5}$ and PM_{10} levels across low-, middle- and high-income residential areas in the Enugu Metropolis. The authors are not aware of any study in the South-East Nigeria especially Enugu that utilised the World Health Organisation's AirQ+ software to model the potential health burden and attributable disease cases within specific socio-economic contexts. The findings of this study would therefore serve as baseline data for urban cities in South-Eastern Nigeria and give information on the health burden faced by households in different socio-economic groups. The objectives of this study are to measure the indoor concentrations of particulate matter ($PM_{2.5}$ and PM_{10}) across the study area and to assess the potential health burden associated with particulate-matter exposure among both children and adults.

EXPERIMENTAL

Study area: Enugu Urban, the capital of Enugu State in southeastern Nigeria, lies between latitudes 6º30′N and 6º40′N and longitude 7º20′ and 7º35′E, at an elevation of approximately 151.91 m (498.39 feet) above sea level [25]. The city is situated in the sedimentary basin of Eastern Nigeria with two terrains in the region- the escarpment zone and the plains and lowlands of the Cross-River Basin. Enugu is located in the derived savanna climatic belt and is characterised by average temperatures between 26.8 ºC to 32.5 ºC [26].

There are occasional temperature spikes particularly in March which is the hottest month of the year and temperatures can rise to 36 ºC [25]. The annual average rainfall is between 937.2 mm to 2243.3 mm [26]. The city has two distinct seasons, the dry season which occurs from November to March and the wet season which occurs from April to October. The urban city has an estimated population of 876,000 inhabitants [27] residing in 28 layouts across Enugu urban [26].

This study was carried out across three residential layouts *viz*. Ogui new layout, New Haven and Independence layout. These layouts were chosen to represent a range of socio-economic categories with Ogui New layout being a low-income area, New Haven a middle-income area and Independence layout a high-income area with predominantly new buildings. The study area is shown in Fig. 1.

Field data collection: A factory calibrated portable multi-gas analyzer by Bosean Electronic Technology Co., Ltd.

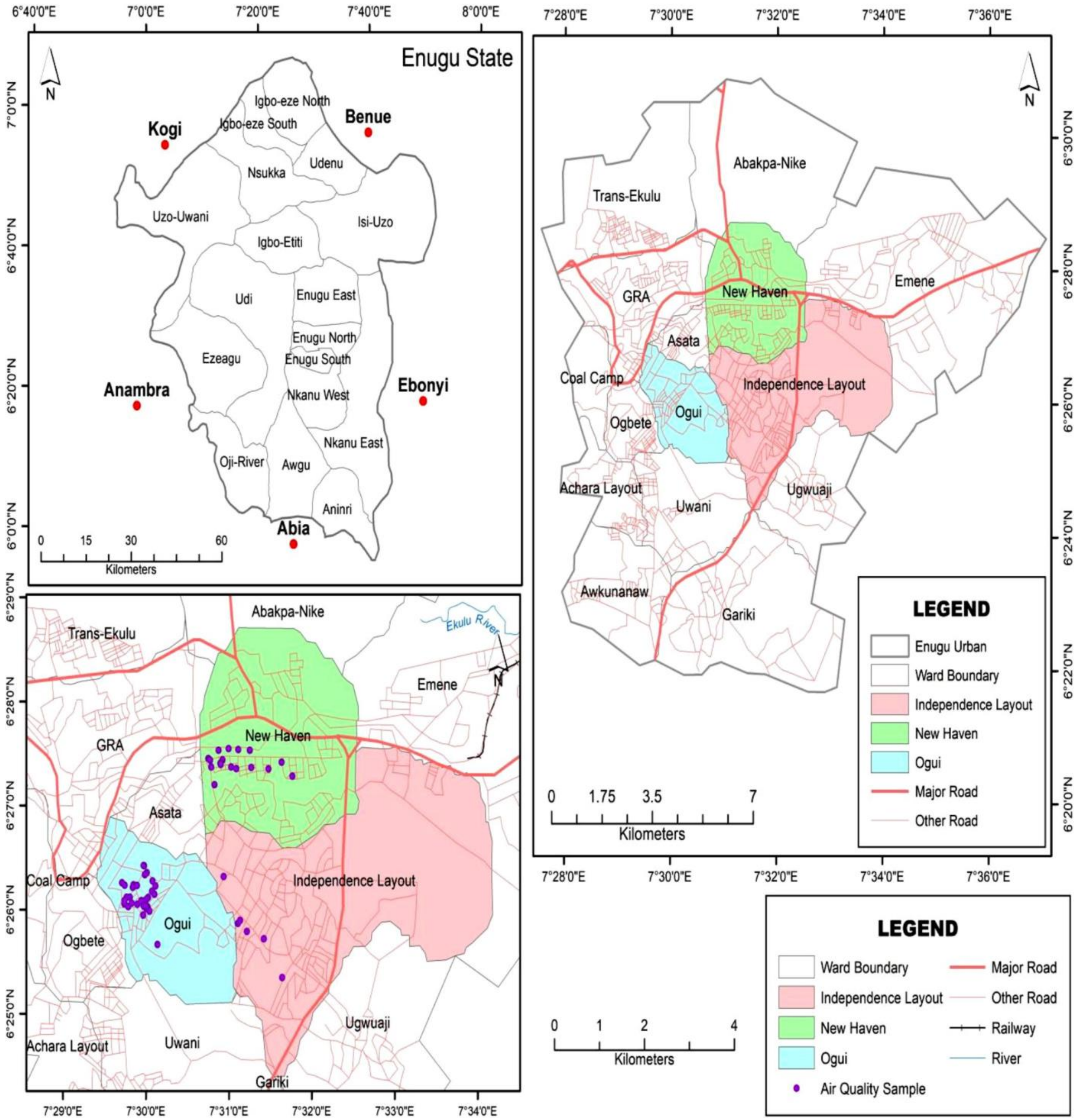

Fig. 1. Map of the study area showing sampling points in Ogui layout, Independence layout and New Haven. Inset: Map of Enugu State showing Enugu Urban

Model version K-600M was employed in the measurement of the concentration of $PM_{2.5}$ and PM_{10}. Detection range for the particulate matter was 0-1000 $\mu g/m^3$. Indoor samplings of the particulate matters were carried out in 53 homes twice a week, during the periods January to May 2024 covering the rainy and dry season. For the physical air quality monitoring, a representative sub-sample was selected. This sub-sampling was necessary to ensure the feasibility of intensive, high-resolution monitoring while maintaining statistical relevance for each socio-economic layout.

The device was placed in the family lounge area and the kitchen or cooking location at a height of 1-1.5 m from the floor. Data was collected three times a day-morning (7 am-10 am), afternoon (1 pm-4 pm) and evening (5-8 pm) and the mean daily concentration was calculated. The sampling schedule was rotated across different days of the week. This rotation ensured that both weekdays and weekends were captured, thereby accounting for variations in household activities such as weekend cooking patterns and increased generator usage during non-work days. Data were analysed using statistical methods to determine correlations between air quality and socio-economic factors.

While portable monitors provide the mobility required for residential indoor sampling and capture real-time fluctuations during specific household activities, however, these devices are not Federal Reference Method (FRM) instruments. Although these sensors are useful for identifying relative trends and differences between residential zones, they may exhibit a greater margin of error compared to stationary gravimetric instruments.

Estimation of potential health burden due to particulate matter exposure by adults: The health burden due to longterm particulate matter exposure was determined using AirQ+ modelling software Version 2.2 designed by the WHO, as prescribed by the WHO Regional Office for Europe [28]. This model calculated the burden of disease attributable to long-term particulate matter exposure for stroke, lung cancer, ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD) and acute lower respiratory infections (ALRI). The software is based on the concentration-response functions from epidemiological studies and the *meta*-analysis of systematic reviews until 2013.

The relative risk (RR) was calculated for long-term exposure to $PM_{2.5}$ for adult cardiopulmonary mortality as well as for lung cancer. The relative risk was calculated using eqn. 1. [29-31]:

$$RR = \left(\frac{X+1}{X_o+1}\right)^{\beta} \quad (1)$$

where X_0 is the threshold concentration of $PM_{2.5}$ (5 μg/m^3 as recommended by WHO 2021 air quality guidelines [18]); X is the pollutant concentration (μg/m^3); and β represents the risk function coefficient or concentration response coefficient. The suggested β coefficient is 0.15515 (95% CI = 0.0562, 0.2541) for cardiopulmonary diseases and 0.23218 (95% CI = 0.08563–0.37873) for lung cancer related mortality.

Estimation of potential health burden due to particulate matter exposure by children: The relative risk for respiratory mortality and short-term exposure to PM_{10} for children aged < 5 years was calculated by using eqn. 2:

$$RR = \exp[\beta(X - X_o)] \quad (2)$$

where X is the baseline concentration of PM_{10} (15 μg/m^3 as recommended by WHO 2021 air quality guidelines) [32,33]; X is the annual mean pollutant concentration for PM_{10} (μg/m^3); and β represents the risk function coefficient or concentration response coefficient. The suggested β coefficient is 0.00166 (95% CI = 0.00034, 0.0030).

RESULTS AND DISCUSSION

Indoor concentration of particulate matter $PM_{2.5}$ and PM_{10} across the study area: The concentration levels for in the air were monitored and analysed. The daily mean concentration levels of $PM_{2.5}$ and PM_{10} for each household in dry and wet season across the independence layouts, New Haven and Ogui New layout are presented in Table-1. The data reveals a seasonal trend, with significantly higher particulate levels recorded during the dry season compared to the wet season. Among the layouts, New Haven recorded the highest average concentrations of $PM_{2.5}$ (58.9 μg/m^3) and PM_{10} (66.90 μg/m^3) during the dry season, while Ogui New layout recorded the highest average concentrations in the wet season, at 33.5 μg/m^3 for $PM_{2.5}$ and 38.3 μg/m^3 for PM_{10}.

TABLE-1
SEASONAL AVERAGE CONCENTRATIONS DATA OF $PM_{2.5}$ AND PM_{10}

	Dry season		Wet season	
	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}
Independence layout	46.2	56.4	24.5	27.8
New Haven	58.9	66.9	26.4	30.1
Ogui New layout	50.2	61.1	33.5	38.3

Thus, in Enugu city, Independence layout is perceived to be a high-brow area because of the level of education of residents, social amenities, building style and the rental cost in the area. A supplementary survey (not shown in this article) indicated that residents of Independence layout generally have higher incomes compared to those in New Haven and significantly higher incomes than those in Ogui New layout. So, the monthly income levels are highest in Independence layout, followed by New Haven, with Ogui New layout having the lowest income levels among the three layouts.

Dry season $PM_{2.5}$ levels: In the dry season, the mean $PM_{2.5}$ levels across the layouts were 46.2 μg/m^3 in Independence layout, 58.9 μg/m^3 in New Haven and 50.2 μg/m^3 in Ogui New layout. New Haven exhibited the highest $PM_{2.5}$ concentrations, while Independence layout recorded the lowest. A one-way ANOVA analysis of $PM_{2.5}$ levels showed significant differences between some of the layouts: specifically, there was a significant difference in $PM_{2.5}$ levels between New Haven and Independence layout. However, there was no significant difference in $PM_{2.5}$ levels between New Haven and Ogui New layout and between Independence layout and Ogui New layout.

The average monthly income for Independence layout, New Haven and Ogui New layout are estimated at 500,000, 200,000 and 100,000 NGN, respectively. From the reported $PM_{2.5}$ values, there appeared to be no association between the income levels and the measured $PM_{2.5}$ concentrations in the dry season. Interestingly, high income levels did not clearly show that increased income leads to significantly lower levels of $PM_{2.5}$. Though Independence layout is an affluent high-brow area where residents primarily use electricity and gas for cooking but this did not result in significantly lower $PM_{2.5}$ levels compared to lower-income areas such as Ogui New layout, where residents more commonly rely on firewood and charcoal. Because there was no statistically significant difference in $PM_{2.5}$ levels for the high-income area (Independence layout) and low-income area (New Ogui layout), income levels seem not to play any role in affecting $PM_{2.5}$ in these two locations in the dry season. This means that from the present results, income levels do not have any relationship with $PM_{2.5}$ levels in the dry season. It is therefore possible that the $PM_{2.5}$ levels may be substantially contributed by dust particles coming from the ambient environment.

Dry season PM_{10} levels: The average PM_{10} concentrations recorded during the dry season were 56.4 μg/m^3, 66.9

μg/m^3 and 61.1 μg/m^3 in Independence layout, New Haven and Ogui New layout, respectively. Although New Haven showed the highest PM_{10} levels, a one-way ANOVA analysis indicated no significant difference in PM_{10} concentrations across the layouts. The different layouts have varied income levels and again it can be observed that income level did not play any significant role in the levels of PM_{10} pollutant measured in the households in these areas as the concentration levels of PM_{10} in the areas were not significantly different.

Wet season $PM_{2.5}$ levels: During the wet season, the average $PM_{2.5}$ concentrations were markedly lower, with mean values of 24.5 μg/m^3, 26.4 μg/m^3 and 33.5 μg/m^3 in Independence layout, New Haven and Ogui New layout, respectively. Statistical analysis using a one-way ANOVA revealed a significant difference in $PM_{2.5}$ levels between Independence layout and Ogui New layout. However, no significant differences were observed between New Haven and Independence layout and between New Haven and Ogui New layout.

From the reported $PM_{2.5}$ values in the wet season, it appeared that the lower income Ogui New layout had significantly higher levels of $PM_{2.5}$ than Independence layout in the wet season. This difference may be linked to the structural and socioeconomic characteristics of the layouts. In low-income areas such as Ogui New layout, housing is often less ventilated, with limited windows and doors and higher occupancy density which are frequently kept shut during the rainy season to prevent water intrusion. Also, the residents in these areas resort to cooking indoors all the time unlike during the dry season when some cooking can take place. Owing to the limited access to cleaner fuel by the residents of Ogui New layout, solid fuels, such as charcoal and kerosene are mainly used during the dry season. These practices likely contribute to higher indoor $PM_{2.5}$ levels in Ogui New layout during the wet season.

Wet season PM_{10} levels: The average PM_{10} concentrations during the wet season were 27.8 μg/m^3 in Independence layout, 30.1 μg/m^3 in New Haven and 38.3 μg/m^3 in Ogui New layout. The results indicated that Ogui New layout had the highest PM_{10} levels whereas Independence layout had the lowest value. One-way ANOVA analysis revealed a significant difference in PM_{10} levels between Ogui New layout and Independence layout while no significant differences were found between New Haven layout and either of the other two layouts.

These results indicate that similar to the dry season $PM_{2.5}$ and PM_{10} concentrations in the wet season were significantly higher in Ogui New layout, the low-income area. The present findings align with patterns observed in other studies [34,35], where low-income urban areas frequently exhibit higher particulate levels, potentially due to poorer ventilation, reliance on solid fuels and more frequent indoor cooking during adverse weather.

In comparing this study with studies in other southern parts of Nigeria shows that in Ogbomoso, Nigeria, mean indoor concentrations of 27.7 and 41.6 μg/m^3 for $PM_{2.5}$ and PM_{10}, respectively during the wet season has been reported [36]. Eghomwanre *et al.* [37] in his study in Edo, Nigeria found that average concentrations of indoor and ambient particulate matter range from 27.4-59.6 μg/m^3 for $PM_{2.5}$ and 33.5-67.9 μg/m^3 for PM_{10} in the wet and dry seasons. Another study in Aba, Abia State Nigeria found that indoor $PM_{2.5}$ concentrations ranged from 47.5 μg/m^3 to 80.0 μg/m^3 in households that utilised low grade fuels while households using liquified petroleum gas (LPG) had $PM_{2.5}$ concentration levels of 33.0 to 112.5 μg/m^3. The $PM_{2.5}$ personal exposures were 152.3 μg/m^3 and 58.3 μg/m^3 for the low-grade fuel users and LPG-users, respectively. Another study conducted in Northern part of Nigeria reported average $PM_{2.5}$ and PM_{10} levels in residential buildings of 83.31 μg/m^3 and 103.71 μg/m^3, respectively [30]. These studies show wide variations of results of indoor concentrations of particulate matter. These differences can be attributed to geographic location, peculiar cultural/ethnic behaviours relating to cooking activities and seasonal variations, which influence both the type and amount of PM in indoors. Some cities in Nigeria also experienced higher particulate concentrations due to increased dust blown in from the Sahara-desert particularly during the dry harmattan season, when dry and dusty trade winds transport particles across the area. Furthermore, variations in local fuel types for cooking, ventilation practices and building structures contribute to these differences. Therefore, the disparities observed highlight the need for region-specific interventions that consider local environmental conditions and socio-economic factors impacting the indoor air quality.

The present findings differed from the study by Garg & Ghosh [38] and Gupta *et al.* [39] that reported poorest indoor air quality in the high-income groups followed by the low-income group and then the middle-income group having the best indoor air quality. It would appear that in these studies the higher income which was linked to more modern conveniences and amenities resulted in reduced indoor air quality. However, Adamkiewicz *et al.* [40] reported elevated indoor concentrations of various air pollutants in low-socioeconomic status households due to the outdoor sources and poorer physical structures which tend to agree with the findings of this study.

Burden of disease due to household air pollution in studied areas according to income: The AirQ+ software was employed using the variables as indicated in Table-2. The annual $PM_{2.5}$ average concentration was the average from the dry and wet seasons monitoring. The incidence rate for ALRI in Nigeria was obtained from UNICEF, 2022 [41] while lung cancer incidence was from International Agency for Research on Cancer [42]. The age-standardised incident rates was obtained from the Global Burden of Disease study, 2021 [22] by the Institute for Health Metrics and Evaluations. The layouts in Enugu urban were grouped according to population density (Table-3). The high-density areas were taken to be low-income layouts, the medium-density areas were assumed to be middle-income layouts and the low-density layouts were assumed to be high-income layouts.

The variables and the results of the burden of disease analysis are presented in Tables 2 and 4. The results show that lung cancer has a relatively lower attributable cases due to air pollution per 100,000 population. However, it shows an average of about 20% risk of lung cancer attributable to $PM_{2.5}$ concentrations in the studied area. This is notably important for residents in the middle-income areas who have about 17% of estimated lung cancers cases in both males and females

TABLE-2
VARIABLES USED IN BURDEN OF DISEASE CALCULATIONS ON AirQ+

Population group	Health outcome of interest	Population	Pop. at risk (%)	Area (km^2)	$PM_{2.5}$ annual average conc.	Incidence (100,000 pop)	Rel. risk	Lower conf. int RR	Upper conf int. RR
High-income layouts									
Children <5 years	Acute Lower Resp. Infection	118185	15.4	10.87	46.24	2200	1.05	1.01	1.08
Adults >30 years	Chronic obs. pul. disease	118185	34	10.87	46.24	142.02(m), 98.95(f)	1.32	1.11	1.58
Adults >30 years	Ischemic heart dis.	118185	34	10.87	46.24	154.07 (m), 144.67 (f)	1.32	1.11	1.58
Adults >30 years	Stroke	118185	34	10.87	46.24	65.52(m), 66.98(f)	1.32	1.11	1.58
Adults >30 years	Lung cancer	118185	34	10.87	46.24	4.3(m), 3.6 (f)	1.52	1.17	1.98
Middle-income layouts									
Children <5 years	Acute Lower Resp. Infection	312953	15.4	8.25	58.96	2200	1.06	1.01	1.10
Adults >30 years	Chronic obs. pul. disease	312953	34	8.25	58.96	142.02(m), 98.95(f)	1.36	1.12	1.66
Adults >30 years	Ischemic heart dis.	312953	34	8.25	58.96	154.07 (m), 144.67 (f)	1.36	1.12	1.66
Adults >30 years	Stroke	312953	34	8.25	58.96	65.52 (m), 66.98(f)	1.36	1.12	1.66
Adults >30 years	Lung cancer	312953	34	8.25	58.96	4.3(m), 3.6 (f)	1.59	1.19	2.12
Low-income layouts									
Children <5 years	Acute Lower Resp. Infection	989003	15.4	6.93	50.22	2200	1.06	1.01	1.11
Adults >30 years	Chronic obs. pul. disease	989003	34	6.93	50.22	142.02(m), 98.95(f)	1.36	1.12	1.65
Adults >30 years	Ischemic heart dis.	989003	34	6.93	50.22	154.07 (m), 144.67 (f)	1.36	1.12	1.65
Adults >30 years	Stroke	989003	34	6.93	50.22	65.52 (m), 66.98(f)	1.36	1.12	1.65
Adults >30 years	Lung cancer	989003	34	6.93	50.22	4.3(m), 3.6 (f)	1.58	1.18	2.11

TABLE-3
POPULATION OF LAYOUTS IN ENUGU URBAN GROUPED BY POPULATION DENSITY

Neighborhoods	Neighborhood density	1991 Census	2024 Projected population
Abakpa	High	90,619	260515.902
Asata	High	21,828	62752.1945
Iva valley	High	8,891	25560.2786
Akwuke	High	3,326	9561.74633
Coal Camp/Ogbete	High	25,994	74728.8136
Ogui New/layout	High	41,237	118550.13
Emene	High	79,033	227207.907
Gariki Awkunanaw	High	19,662	56525.2725
Obiagu	High	5,487	15774.2941
Amechi Awkunanaw	High	13,441	38640.8396
Nike	High	34501	99185.1504
			989002.529
Achara layout	Medium	50,427	144969.989
Maryland	Medium	4,666	13414.0434
Uwani	Medium	31875	91635.798
New Haven	Medium	18,753	53912.0351
Idaw River	Medium	3138	9021.2748
			312953.14
GRA	Low	19,600	56347.0319
Independence layout	Low	10,036	28851.9802
Trans Ekulu	Low	11,474	32986.0124
			118185.025

attributable to the household air pollution. This higher risk of lung cancer indicates increased probability of the presence of carcinogenic pollutants in the area. This highlights the need for regulation and control measures on sources of household air pollution and adequate air quality monitoring.

The occurrence of stroke, a major cardiovascular disease, is still a major challenge in countries like Nigeria. The results showed significant burden across the residential layouts with an estimated number of attributable cases per 100,000 population of between 5 to 24 cases per 1000,000 population with the highest number of cases occurring in the middle-income and low-income layouts. The $PM_{2.5}$ attributable mortality in adults above 30 years due to stroke is between 4-16.5% in the high-income group and 4-18% in the low-income and middle-income groups.

The burden of disease due to chronic obstructive pulmonary disease is also noticeably higher among men in middle-income and low-income layouts (15.5% in men and 11% in women in the middle and low-income groups). The $PM_{2.5}$ attributable mortality due to COPD is about 10% (95% CI: 3.6%-16.5%) in high income groups and 11% (95 CI: 4-18%), with 26.28 (95% CI: 9.5-44) deaths in adults over 30 years 5 per 100,0000 population. The low-income group had an estimated 52 (95% CI: 19-86) cases of mortality at current population levels that are attributable to air pollution. This result suggests a considerable burden of COPD in the city and indicates a relationship between lower economic status and a vulnerability to air pollution related diseases. This situation could have been worsened by poorer living conditions, higher exposure to air pollutants from household sources and ambient sources; as well as limited access to health services which is usually experienced by lower socio-economic classes of the society.

Acute lower respiratory infections in children less than 5 years old showed a significant burden across all the residential layouts with a combined mortality of 57.63 cases per 100,000. The highest number of cases occurred in the middle and low-income layouts with an estimated 20.14 attributable deaths per 100,000 at risk. At the present population level, the estimated mortality was 31 (C.I. 5-56) deaths in the low-income layout and 10 (95% CI: 2-16) deaths. The high incidence of diseases such as chronic obstructive pulmonary disease in adults and acute lower respiratory infections in children

TABLE-4
RESULTS FROM BURDEN OF DISEASE CALCULATIONS

	Disease	Estimated attributable proportion (%) Cntr (95% C.I.)	Est. number of attributable cases Cntr (95% C.I.)	Est. number of attribut. cases per 100,000 pop at risk Cntr (95% C.I.)
High-income layouts	Lung cancer (F)	15.02 (5.46-24.99)	0	0.54 (0.20-0.90)
	Lung cancer (M)	15.02 (5.46-24.99)	0	0.65 (0.23-1.07)
Middle-income layouts	Lung cancer (F)	16.71 (6.07-27.58)	1 (0-1)	0.60 (0.22-0.99)
	Lung cancer (M)	16.71 (6.07-27.58)	1 (0-1)	0.72 (0.26-1.19)
Low-income layouts	Lung cancer (F)	16.47 (5.77-27.4)	2 (1-3)	0.59 (0.21-0.99)
	Lung cancer (M)	16.47 (5.77-27.4)	2 (1-4)	0.71 (0.25-1.18)
High-income layouts	Stroke (F)	3.61-16.47	1-4	2.41-11.03
	Stroke (M)	3.61-16.47	1-4	2.36-10.79
Middle-income layouts	Stroke (F)	3.92-18.33	3-13	2.63-12.28
	Stroke (M)	3.92-18.33	3-13	2.57-12.01
Low-income layouts	Stroke (F)	3.92-18.1	9-41	2.63-12.12
	Stroke (M)	3.92-18.1	9-40	2.57-11.86
High-income layouts	COPD (F)	9.81 (3.61-16.47)	4 (1-7)	9.71 (3.57-16.30)
	COPD (M)	9.81 (3.61-16.47)	6 (2-9)	13.94 (5.12-23.39)
Middle-income layouts	COPD (F)	10.91 (3.92-18.33)	11 (4-19)	10.79 (3.88-18.13)
	COPD (M)	10.91 (3.92-18.33	16 (6-28)	15.49 (5.57-26.03)
Low-income layouts	COPD (F)	10.91 (3.92-18.1)	36 (13-60)	10.79 (3.88-17.91)
	COPD (M)	10.91 (3.92-18.1)	52 (19-86)	15.49 (5.57-25.71)
High-income layouts	IHD (F)	3.61-16.47	2-10	5.22-23.83
	IHD (M)	3.61-16.47	2-10	5.55-25.38
Middle-income layouts	IHD (F)	3.92-18.33	6-28	5.67-26.51
	IHD (M)	3.92-18.33	6-30	6.04-28.24
Low-income layouts	IHD (F)	3.92-18.1	19-88	5.67-26.19
	IHD (M)	3.92-18.1	20-94	6.04-27.89
High-income layouts	ALRI	0.76 (0.15-1.22)	3 (1-5)	16.81 (3.38-26.77)
Middle-income layouts	ALRI	0.92 (0.15-1.52)	10 (2-16)	20.14 (3.38-33.37)
Low-income layouts	ALRI	0.92 (0.15-1.67)	31 (5-56)	20.14 (3.38-36.65)

highlight the need for interventions targeting at improving not just household air quality but also ambient air quality. The children less than 5 years are particularly vulnerable to the effects of harmful pollutants in the air.

The estimated attributable cases of mortality from lung cancer were 2 per 100,000. With a total of 6 cases of lung cancer in men and women estimated to be attributable to $PM_{2.5}$ in the study area. The findings estimate 39-182 cases of ischemic heart disease (IHD) in the low-income layouts with 12-58 cases and 4-20 cases of IHD occurring in men and women in the middle-income and high-income layouts respectively.

In summary, for Enugu urban, the $PM_{2.5}$ attributable crude mortality due to ALRI, COPD, lung cancer, IHD and stroke on average across the residential layouts is estimated to be 44, 125, 6, between 4-182 and between 1-40 deaths, respectively with the age-standardised mortality of 57, 76, 4, between 10.77-54.75 and between 4.77-24.29. These findings were similar to the findings of Moradi *et al.* [43], who found the total number of deaths to be 73, 11, 7, 15 and 14 deaths, respectively, for ALRI, COPD, lung cancer, IHD and stroke. The burden of disease numbers will differ based on population risk level and incidence rates for the location.

However, the mortality figures from the burden of disease calculations were less than those from Balidemaj *et al.* [44]. Their results from studying Adama women in Ethiopia estimated burden of disease mortality for ALRI, COPD, IHD, LC and stroke as 89, 13, 34, 51 and 18, respectively with the mortality rates per 100,000 women in Ethiopia being 25, 4, 10, 14 and 5 for ALRI, COPD, IHD, LC and stroke, respectively. This study had higher mortality values due to the three-quarters of the study population utilised solid cooking fuel in the households.

Conclusion

The indoor $PM_{2.5}$ and PM_{10} concentration values in Independence layout, New Haven and Ogui New layouts of Enugu State Nigeria in wet and dry seasons of 2024 were determined with a view to ascertaining the health burden on the residents of these areas with respect to COPD, IHD and ALRI. These residential areas, Independence layout, New Haven and Ogui New layout represent high, middle- and low-income areas, respectively. Independence layout, a high- income area only had statistically significant lower levels of $PM_{2.5}$ and PM_{10} than Ogui New layout (low-income area) during the wet season. The $PM_{2.5}$ and PM_{10} concentration values were higher in dry season than in wet season and were higher than world health threshold values for protection of public health. About 10 people are likely to suffer chronic obstructive pulmonary disease (COPD) in Independence layout whereas for the middle- and low-income areas (New Haven and Ogui New layouts) about 15 people suffer COPD. The study revealed that about 5 and 16 people are likely to suffer from ischemic heart disease (IHD) and acute lower respiratory infections (ALRI), respectively in Independence layout whereas for

Ogui New layout and New Haven, 6 and 20 people will suffer IHD and ALRI respectively. These numbers are worrisome and justify the urgent formulation and implementation of measures by the government to reduce airborne particulate matter in the study area. The health burden results presented in this study, also provide critical insights into the potential impact of particulate matter on the residents of Enugu, Nigeria. It is, however, worth noting that the results generated by AirQ+ are modeled health estimates based on standardised concentration-response functions and are not derived from direct clinical records or hospital admissions from the sampled homes. Consequently, while these findings indicate a significant potential public health risk, they should be interpreted as estimates of probability. The validation of these modelled outcomes through longitudinal clinical studies and local hospital data represents a vital area for future research. Furthermore, the AirQ+ model assumes that the concentration-response functions (CRFs) derived from global *meta*-analyses are applicable to the local population of Enugu. While these are the most validated tools available, uncertainties may arise in the assumption of a linear relationship between exposure and health outcomes at high concentrations. Future studies incorporating local epidemiological cohorts would further refine these estimates.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language. The authors reviewed and edited the content and take full responsibility for the published work.

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