

POPULATION-WEIGHTED ASSESSMENT OF SPATIAL PATTERNS AND POPULATION-WEIGHTED EXPOSURE TO ATMOSPHERIC POLLUTION IN NORTHWESTERN NIGERIA

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ABSTRACT

Atmospheric pollution poses a significant environmental concern in Northwestern Nigeria, where differences in population concentration, human activities, biomass combustion, and regional dust processes create unequal exposure across states. This study assessed the spatial patterns and population-weighted exposure to major atmospheric pollutants across Northwestern Nigeria. Data on PM_{2.5}, PM₁, SO₂, CO, O₃, and aerosol optical depth data were from NASA atmospheric and satellite products, while population estimates were obtained from the National Bureau of Statistics. The analysis also used Ground-based air quality observations and administrative boundary data. The datasets underwent spatial alignment, extraction, aggregation, and population weighting. Descriptive statistics assessed pollutant exposure, whereas Pearson correlation analyzed relationships between population density and PM_{2.5} exposure as well as between aerosol optical depth (AOD) and PM_{2.5}. The study employed RMSE to assess the agreement between gridded and ground-based observations. Spatial analysis revealed both population exposure vulnerability and overall exposure metrics. Model evaluation employed RMSE, R², and prediction accuracy. Kano and Sokoto recorded the highest population-weighted exposure, whereas Kebbi had the lowest. Kano combined high population density with elevated particulate exposure, whereas exposure in Sokoto and Jigawa may reflect the additional influence of Harmattan dust, biomass combustion, and regional aerosol transport. Biomass fuel users had the highest estimated exposure among the vulnerable groups assessed. Extra Trees achieved the strongest predictive performance. The study highlights that population exposure results from the combined effects of population distribution, local emissions, and regional atmospheric dynamics. It recommends source-specific emission controls, cleaner household energy, stronger air quality monitoring, and targeted interventions in persistent exposure hotspots.

Keywords: Atmospheric pollution; population-weighted exposure; PM_{2.5}; Northwestern Nigeria; exposure hotspots; air quality

INTRODUCTION

Air pollution is a major environmental risk to human health, with particulate and gaseous pollutants affecting populations in both urban and rural environments (Chen et al., 2024). Among these pollutants, fine particulate matter (PM_{2.5}), particles with an aerodynamic diameter of 2.5 µm or less, is of particular concern because it can penetrate deep into the respiratory tract and contribute to cardiovascular and respiratory diseases (Xing et al., 2016). The World Health Organization (WHO) estimates that

ambient air pollution contributes to approximately 4.2 million premature deaths annually worldwide, while the combined effects of ambient and household air pollution are associated with approximately 7 million premature deaths each year (Adamkiewicz et al., 2020). The burden is not distributed equally because exposure varies according to pollutant concentrations, population distribution, socioeconomic conditions, household energy use, urban development, and local environmental characteristics (Sohrabi et al., 2020).

The magnitude of exposure is particularly important in rapidly urbanising countries where population growth is occurring alongside increasing transportation, industrial activity, energy demand, and household fuel consumption (Audi et al., 2026). The WHO annual guideline for PM_{2.5} is 5 µg/m³, while the 24-hour guideline is 15 µg/m³. Concentrations above these levels indicate increasing population exposure to particulate pollution (Pai et al., 2022). However, assessing exposure using pollutant concentration alone can provide an incomplete picture of the actual population burden. A location with a high concentration but a small population may contribute less to total population exposure than a densely populated area with a lower concentration (Otu et al., 2026). Population-weighted exposure therefore provides a more appropriate basis for identifying locations where pollutant concentrations coincide with large numbers of exposed people (Gamal et al., 2026).

This issue is particularly important in Africa, where urban populations are expanding rapidly while air quality monitoring networks remain limited. Africa has experienced substantial urban growth over recent decades, with the urban population projected to continue increasing throughout the coming decades (Jiang et al., 2025). Rapid urbanisation is accompanied by increasing road traffic, industrialisation, electricity generation, construction, waste burning, and household dependence on solid fuels (Seun et al., 2022). In many cities, these sources operate alongside naturally occurring dust and biomass burning, producing complex mixtures of particulate and gaseous pollutants (Abulude et al., 2024). Limited monitoring stations make it difficult to characterise these patterns continuously across large areas (Mahmud et al., 2023). Satellite observations, atmospheric models, reanalysis products, and ground observations therefore provide important opportunities for developing spatially continuous assessments of air pollution exposure (Yusuf & Sa'id, 2023).

Nigeria presents a particularly important case because of its large population, rapid urban growth, expanding transport networks, industrial activities, widespread use of petrol and diesel generators, open waste burning, and continued dependence on biomass fuels

(Olise, 2025; Pona et al., 2021). The 2022 Nigerian Multidimensional Poverty Index reported that 63% of Nigerians were multidimensionally poor, with energy access and living conditions forming important dimensions of deprivation (Akoji & Abaji, 2025). Dependence on solid fuels remains common in many households, particularly in rural and low-income communities, creating potential exposure to particulate matter and carbon monoxide (Sani et al., 2025). At the same time, urban populations are exposed to emissions from traffic, industries, commercial activities, generators, construction, and waste combustion (Abulude et al., 2024). These sources vary considerably across locations, making a regional population exposure assessment necessary rather than relying only on evidence from individual urban centres. Northern Nigeria has additional exposure pathways associated with its climatic and geographical setting (Okon et al., 2021). The region is influenced by the seasonal movement of mineral dust from the Sahara and Sahel (Ayanlade et al., 2019). During the Harmattan period, dry conditions and strong northeasterly winds can transport large quantities of mineral dust into populated areas (Burton et al., 2013). This regional dust can combine with locally generated emissions from vehicles, industries, household combustion, agricultural activities, and open burning (Okedere et al., 2021). Consequently, particulate pollution in northern Nigeria cannot be attributed exclusively to urban emissions (Lala et al., 2023). The interaction between regional dust transport and local emission sources contributes to substantial spatial variations in population exposure, with seasonal conditions further influencing exposure intensity.

Previous studies have documented elevated particulate pollution in different parts of northern Nigeria (Lala et al., 2023; Omokungbe et al., 2026; Shittu et al., 2025). Research in Kano has reported substantial concentrations of PM_{10} , $PM_{2.5}$, and PM_{10} , with pollution influenced by traffic, industrial activity, biomass combustion, and seasonal dust conditions (Abuchi et al., 2025; Idris et al., 2025). Studies in Kaduna have similarly identified contributions from industrial and combustion-related sources (Okedere et al., 2021) while research in Sokoto and other Sahelian locations has highlighted the importance of Harmattan dust and regional aerosol transport. These studies provide important evidence of local pollution conditions, but their geographical coverage and study periods vary (Anuforom, 2007). Much of the existing research has also concentrated on individual cities or individual pollutants rather than examining population-weighted exposure to multiple atmospheric pollutants across the wider Northwestern Nigeria region (Amaechi et al., 2024; Hamidu et al., 2021; Sadiq et al., 2022).

Northwestern Nigeria provides a particularly suitable setting for a regional exposure assessment because it combines densely populated urban centres with extensive rural and agricultural areas and contrasting environmental conditions (Mahmud et al., 2023). The region comprises Kaduna, Kano, Katsina, Kebbi, Sokoto, Jigawa, and Zamfara States. Kano is one of the largest urban and commercial centres in northern Nigeria, with extensive transportation, industrial, and commercial activities (Koko et al., 2023). Kaduna contains major industrial and transportation corridors, while Sokoto, Katsina, Jigawa, and Zamfara face varying combinations of regional dust, agricultural activities, biomass combustion, and urban emissions (Abdullahi, 2025). Kebbi contains comparatively extensive rural and agricultural landscapes (Raji et al., 2020). These differences can create substantial spatial inequalities in population exposure. Seasonal conditions add a

dimension to this spatial exposure pattern. The dry season in northern Nigeria is associated with low rainfall, Harmattan conditions, increased dust mobilisation, agricultural residue burning, bush burning, and biomass combustion (Ochei & Adenola, 2018). Rainfall during the wet season can remove atmospheric particles through wet deposition and alter atmospheric mixing conditions (Sukchinda et al., 2026). Previous studies in northern Nigeria have reported higher particulate and aerosol concentrations during the dry and Harmattan seasons than during the wet season (Nwokorie et al., 2026). However, seasonal variations in pollutant concentration do not necessarily translate into equivalent population exposure because the number and distribution of exposed people also vary spatially. Understanding these differences matters because periods of increased pollution may coincide with greater exposure among populations in densely settled areas and among groups that depend on biomass fuels.

The limited number of ground-based monitoring stations across Northwestern Nigeria further strengthens the need for integrated spatial approaches (Mahmud et al., 2023). Satellite-derived aerosol observations and other remotely sensed products can provide broader spatial coverage, while modelled and reanalysis datasets can help characterise pollutant locations without direct measurements (Yusuf & Sa'id, 2023). When combined with population data, these sources can help identify areas where elevated pollutant concentrations coincide with larger exposed populations beyond the coverage of conventional monitoring networks. However, the reliability of such assessments depends on the datasets and careful consideration of spatial differences among the data sources. Despite growing evidence of atmospheric pollution in northern Nigeria, regional evidence remains limited on how the spatial distribution of multiple pollutants translates into population exposure across Northwestern Nigeria. Existing studies have largely focused on individual cities, individual pollutants, or specific pollution sources, leaving limited understanding of the combined population exposure burden across the seven states. This study addresses this gap by assessing spatial patterns and population-weighted exposure to atmospheric pollution across Northwestern Nigeria. The study integrates satellite-derived, ground-based, modelled, and population datasets to assess exposure to $PM_{2.5}$, PM_{5} , PM_{10} , SO_2 , CO , O_3 , and aerosol optical depth (AOD). Specifically, the study aims to (i) characterise the spatial distribution of major atmospheric pollutants, (ii) quantify population-weighted exposure across Northwestern Nigeria, (iii) examine seasonal differences in exposure between dry and wet periods, (iv) assess the relationship between population density and $PM_{2.5}$ exposure, (v) identify major and persistent population exposure hotspots, and (vi) assess exposure among selected vulnerable population groups. The study provides a regional framework for understanding where atmospheric pollution is concentrated and, more importantly, where elevated concentrations coincide with larger populations and potentially greater exposure burdens.

MATERIALS AND METHODS

Data Used and Sources

The study used atmospheric pollution data, population data, demographic and socioeconomic data, administrative boundary data, and ground-based air quality observations. These datasets were integrated to assess the spatial and seasonal patterns of population-weighted exposure to atmospheric pollution across

Northwestern Nigeria. The atmospheric pollution datasets comprised particulate matter with aerodynamic diameters of 2.5 μm and 1 μm ($\text{PM}_{2.5}$ and PM_{10}), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and aerosol optical depth (AOD). Atmospheric datasets were obtained from the National Aeronautics and Space Administration (NASA), including the Modern Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) and other relevant satellite-derived products used in the study. The monthly gridded data used in this study examine the spatial and temporal distribution of the selected atmospheric pollutants. Population data were obtained from the National Bureau of Statistics (NBS), Nigeria. Population estimates and projections were obtained for Kaduna, Kano, Katsina, Kebbi, Sokoto, Jigawa, and Zamfara States to calculate population density and population-weighted exposure. Population estimates for the analysis periods were matched with the atmospheric pollution data to account for differences in the population exposed to pollution among the seven states.

Demographic and socioeconomic information used to characterise selected population groups was obtained from relevant NBS household and demographic surveys. The NBS Multiple Indicator Cluster Survey contains demographic information on household members and a dedicated dataset for children under five years of age. It also contains household information on the main type of cooking fuel used, including wood, charcoal, agricultural residues, animal dung, and other fuels. NBS Multidimensional Poverty Index Survey was also considered for information on household socioeconomic conditions and cooking fuel use. These data were used to characterise selected groups that may experience greater exposure to air pollution. They were not treated as spatial population surfaces unless the data could be spatially matched to the pollution estimates. Administrative boundary data were used to delineate Kaduna, Kano, Katsina, Kebbi, Sokoto, Jigawa, and Zamfara States. The boundaries define the study area, extract atmospheric pollution data for each state, and aggregate the gridded pollution estimates to the state level. Ground-based observations were used to assess the accuracy of atmospheric pollution estimates. Ground-based air quality observations were used to assess the correspondence between the atmospheric pollution estimates and measured concentrations. Before validation, we matched observations for $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO , and O_3 with the corresponding gridded datasets by location and observation period. The study covered 1995 to 2025, subject to the availability of each atmospheric dataset. Monthly observations constituted the primary temporal unit and were aggregated into annual and seasonal datasets. In this region, the dry season runs from November to April, whereas the wet season lasts from May to October.

Method of Data Analysis

The atmospheric pollution datasets quantify and map the spatial distribution of $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO , O_3 , and aerosol optical depth across the seven states. Monthly observations were aggregated to derive mean pollutant concentrations, and the resulting values were spatially extracted within the administrative boundaries of Kaduna, Kano, Katsina, Kebbi, Sokoto, Jigawa, and Zamfara States. Spatial interpolation and raster analysis generated continuous pollutant surfaces; zonal statistics were used to derive state-level pollutant estimates. The resulting spatial values were classified according to the adopted concentration thresholds and mapped in ArcGIS 10.4 to determine the geographical

concentration of atmospheric pollution. The study derived population-weighted exposure by integrating pollutant concentration data with state-level demographic estimates from the National Bureau of Statistics. For each pollutant, concentrations were weighted by the corresponding state's population to estimate the population exposure burden. This procedure was applied to $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO , O_3 , and extended to aerosol optical depth. Subsequent analysis involved comparing annual exposure estimates across Kaduna, Kano, Katsina, Kebbi, Sokoto, Jigawa, and Zamfara States. Seasonal exposure was derived by separating the observations into dry season, November to April, and wet season, May to October, and calculating population-weighted exposure for each season.

To evaluate the association between population density and $\text{PM}_{2.5}$ exposure levels, Pearson correlation analysis was applied. Population density was calculated as the ratio of state population estimates to land area, and subsequently analyzed against population-weighted $\text{PM}_{2.5}$ exposure. The correlation coefficient determined the strength and direction of the association. Similarly, Pearson correlation analysis quantified the relationship between paired aerosol optical depth and $\text{PM}_{2.5}$. The accuracy of the gridded pollution estimates was assessed by comparing them with corresponding ground-based observations. Pearson correlation measured agreement between the two datasets, whereas Root Mean Square Error assessed the size of the prediction error. These metrics evaluated the reliability of the gridded estimates for pollutants with available ground observations. Exposure levels among children under five years, older adults, pregnant women, biomass fuel users, and low-income households were quantified by linking the available National Bureau of Statistics demographic and socioeconomic information with the corresponding $\text{PM}_{2.5}$ exposure estimates. Exposure values were calculated and compared among the identified groups, after which the groups were assigned to the adopted exposure categories based on their estimated exposure levels.

Population exposure hotspots were identified by analysing the spatial distribution of population-weighted $\text{PM}_{2.5}$. Exposure values were classified according to the adopted thresholds, and areas falling within the higher exposure classes were extracted as hotspots. Hotspot persistence was quantified by examining the recurrence of elevated population-weighted $\text{PM}_{2.5}$ across the analysed periods. The frequency of hotspot occurrence was used to distinguish persistent hotspots from areas with occasional elevated exposure. Positive exposure anomalies were identified from monthly population-weighted $\text{PM}_{2.5}$ observations. A long-term mean was computed separately for each calendar month, and each monthly observation was compared with the corresponding monthly reference value. Observations exceeding the long-term monthly mean were classified as positive anomalies. The number and spatial distribution of positive anomalies were calculated to identify locations with repeated departures and higher exposure. A Composite Population Exposure Index was generated by integrating the standardised population-weighted exposure measures for the assessed pollutants. Each exposure variable was transformed to a common scale before allowing the different pollutants to contribute to a common index. The composite values were calculated for each state and classified into Very Low, Medium, High, and Very High categories. The resulting index was spatially analysed and mapped to compare the overall population exposure burden across the study area. The predictive component used Linear Regression, Random Forest, Gradient Boosting, and

Extra Trees to model the selected exposure variable. The dataset was divided into training and testing subsets, and each algorithm was fitted using the specified predictor variables. Model performance was quantified using Root Mean Square Error and coefficient of determination, with prediction accuracy calculated where applicable. The models were compared using their error and explanatory performance, and the algorithm producing the lowest

prediction error and highest coefficient of determination was the best-performing model. All spatial analyses and map production were conducted in ArcGIS 10.4, while statistical and machine learning analyses were performed using appropriate analytical software.

RESULT AND DISCUSSION

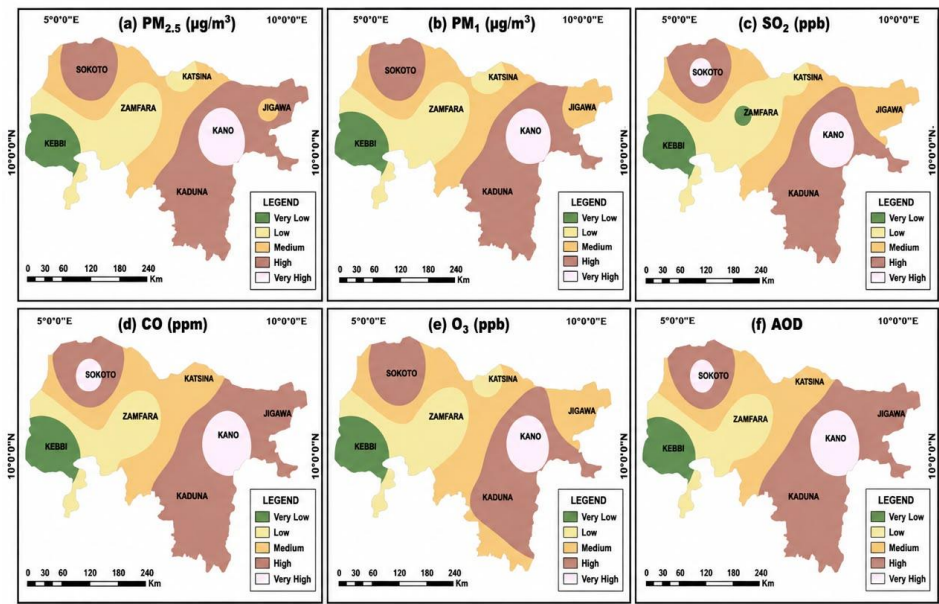


Figure 1: Spatial Distribution of Population Exposure to Major Atmospheric Pollutants Across Northwestern Nigeria

Figure 1 shows clear spatial variation in population exposure to the major atmospheric pollutants across Northwestern Nigeria. The spatial patterns are broadly consistent across $PM_{2.5}$, PM_1 , SO_2 , CO , O_3 , and AOD, with higher exposure concentrated around Kano and Sokoto, while Kebbi records comparatively lower exposure. Kano and Sokoto generally fall within the high to very high exposure categories, indicating substantial population exposure to particulate and gaseous pollutants. Kaduna and Jigawa also show relatively high exposure, while Katsina and Zamfara exhibit moderate to high exposure levels. Kebbi consistently shows the lowest spatial exposure across the pollutant surfaces. The high exposure observed in Kano is likely associated with intensive urban activities, transportation, industrial emissions, and fossil fuel combustion, consistent with Mahmud et al. (2023) and Oji and Adamu (2021). In contrast, the elevated exposure in Sokoto may reflect the influence of Harmattan dust, biomass burning, dry climatic conditions, and regional aerosol transport. (Anuforom et al., 2007). Kaduna also shows relatively high exposure, which may be linked to urban growth, transportation, industrial activities, and fossil fuel combustion, consistent with Ishler et al. (2013). Jigawa falls within the intermediate-to-high exposure range, which may reflect the combined influence of Harmattan dust, biomass combustion, agricultural activities, and regional aerosol movement. The figure suggests that population exposure reflects the combined influence of local anthropogenic emissions and regional atmospheric processes (Ayua et al., 2026).

Table 2: Annual Mean Population-Weighted Exposure Concentrations (1995–2025)

State	PM _{2.5}	PM ₁	SO ₂	CO	O ₃	AOD	Exposure Category
Kaduna	43.8	31.4	8.1	1.3	30.2	0.8	High
Katsina	46.2	33.9	9.1	1.3	31.1	0.8	
Kano	44.7	33.1	9.1	1.4	30.8	0.8	
Katsina	41.5	29.8	8.1	1.2	29.1		Very High
Kebbi	38.9	27.3	7.1	1.2	28.0	0.7	
Sokoto	44.7	31.4	8.1	1.3	30.2	0.8	High
Jigawa	43.8	31.4	8.1	1.3	30.2	0.8	
Zamfara	40.3	28.1	8.1	1.2	29.0	0.7	Moderate-High
Kaduna	43.8	31.4	8.1	1.3	30.2	0.8	

Table 2 shows clear spatial differences in annual population-weighted exposure to atmospheric pollutants across Northwestern Nigeria. Kano and Sokoto recorded the highest overall exposure levels and were classified as Very High, with $PM_{2.5}$ concentrations of 46.2 and 44.7 $\mu g/m^3$, respectively. Kaduna and Jigawa followed with $PM_{2.5}$ concentrations of 43.8 and 43.2 $\mu g/m^3$, while Katsina and Zamfara recorded 41.5 and 40.3 $\mu g/m^3$, respectively. Kebbi recorded the lowest exposure, with a $PM_{2.5}$ concentration of 38.9

$\mu\text{g}/\text{m}^3$, although it remained within the Moderate to High exposure category. The high exposure observed in Kano is consistent with its intensive urbanisation, industrial activities, transportation emissions, and population concentration. In contrast, the relatively high exposure in Sokoto, Katsina, and Jigawa may reflect the combined influence of Harmattan dust transport, biomass burning, agricultural activities, and regional aerosol movement, consistent with Tariq et al. (2023). Kaduna's elevated exposure may be linked more strongly to urban expansion, industrial activities, transportation, and fossil fuel combustion; the relatively lower exposure in Kebbi may reflect differences in urbanisation and industrial activity (Baba, 2025).

The spatial pattern indicates that population exposure was highest in Kano and Sokoto and progressively lower across Kaduna, Jigawa, Katsina, Zamfara, and Kebbi. This pattern is broadly consistent with the pollution hotspots and source patterns identified earlier in the study, particularly the influence of industrial and fossil fuel combustion, biomass burning, and Harmattan dust. The results therefore indicate that population exposure varies considerably across Northwestern Nigeria and that pollution management should consider the dominant sources and environmental conditions of individual states. Targeted emission control, cleaner household energy use, and continued air quality monitoring are therefore important for reducing population exposure across the region (Ajayi & Akanji, 2022).

Table 3: Comparative Performance of Exposure Prediction Models

Model	RMS E	R ²	Prediction Accuracy (%)
Linear Regression	0.71	0.69	72.4
Random Forest	0.36	0.91	91.8
Gradient Boosting	0.33	0.93	93.1
Extra Trees	0.31	0.94	94.2

Table 3 compares the performance of four machine learning models for predicting population exposure to air pollution across Northwestern Nigeria using RMSE, coefficient of determination (R^2), and prediction accuracy. The results show that ensemble learning algorithms outperformed the conventional Linear Regression model, demonstrating greater capability to model the complex relationships between atmospheric pollutants and environmental factors. The Extra Trees model achieved the best overall performance, recording the lowest RMSE (0.31), the highest R^2 (0.94), and the highest prediction accuracy (94.2%). Gradient Boosting ranked second with an RMSE of 0.33, R^2 of 0.93, and prediction accuracy of 93.1%, followed by Random Forest (RMSE = 0.36, R^2 = 0.91, accuracy = 91.8%). In contrast, Linear Regression produced the highest RMSE (0.71), the lowest R^2 (0.69), and the lowest prediction accuracy (72.4%), indicating a comparatively lower ability to represent the nonlinear relationships associated with air pollution exposure.

The higher predictive performance of the ensemble models suggests that population exposure may reflect complex interactions among pollutant concentrations, meteorological conditions, land use, emission sources, and atmospheric processes that can be represented more effectively by nonlinear machine learning approaches. These findings complement the

earlier validation results, which demonstrated strong agreement between satellite-derived and ground-based pollution measurements, further confirming the reliability of the datasets used for exposure modelling.

The results align with Urso et al. (2023), who showed that Random Forest and Extra Trees algorithms outperform traditional statistical models in environmental prediction because of their ability to model nonlinear relationships and variable interactions. Ennaji et al. (2024) reported that Gradient Boosting achieves high predictive accuracy for environmental datasets by iteratively minimizing errors. Falaiye et al. (2025) also found that machine learning techniques produce more accurate air pollution predictions than conventional regression models in Nigeria by effectively integrating multiple environmental variables.

Table 4: Population Density and Pollution Exposure Interaction

State	Estimated Population Density (Persons/km ²)	Mean PM _{2.5} Exposure ($\mu\text{g}/\text{m}^3$)	Exposure Intensity
Kano	520	46.2	Severe
Kaduna	310	43.8	Severe
Katsina	265	41.5	High
Sokoto	240	44.7	Severe
Jigawa	230	43.2	Severe
Zamfara	180	40.3	High
Kebbi	150	38.9	Moderate

Table 4 shows the relationship between population density and PM_{2.5} exposure across Northwestern Nigeria, indicating that population concentration, along with other environmental and anthropogenic factors, influences exposure intensity. Kano recorded the highest population density (520 persons/km²) and the highest PM_{2.5} exposure (46.2 $\mu\text{g}/\text{m}^3$), resulting in a Severe exposure classification. This combination of population concentration alongside intensive urban, industrial, and transportation activities contributes substantially to particulate exposure. Kaduna showed a similar pattern, with a population density of 310 persons/km² and PM_{2.5} exposure of 43.8 $\mu\text{g}/\text{m}^3$, and was also classified as Severe.

However, the relationship was not based on population density alone. Sokoto, for example, had a lower population density of 240 persons/km² than Kaduna but recorded a higher PM_{2.5} exposure of 44.7 $\mu\text{g}/\text{m}^3$ and was classified as Severe. This suggests that regional environmental processes, particularly Harmattan dust transport, biomass burning, and atmospheric aerosol movement, can produce high particulate exposure even where population density is comparatively low. A similar pattern was observed in Jigawa, which had an estimated population density of 230 persons/km² but recorded PM_{2.5} exposure of 43.2 $\mu\text{g}/\text{m}^3$ and was classified as Severe. The relatively high exposure in Jigawa may reflect the combined influence of regional dust transport, biomass burning, agricultural activities, and domestic fuel use.

In contrast, Katsina and Zamfara recorded High exposure, with

PM_{2.5} concentrations of 41.5 and 40.3 µg/m³, respectively, despite their different population densities. Kebbi recorded both the lowest population density (150 persons/km²) and the lowest PM_{2.5} exposure (38.9 µg/m³), resulting in a Moderate classification. This comparatively lower exposure may reflect lower population concentration and less intensive urban and industrial activity relative to Kano and Kaduna. The results demonstrate that population density alone does not determine PM_{2.5} exposure intensity across Northwestern Nigeria. While densely populated and highly urbanised areas such as Kano show a clear combination of high population density and high particulate exposure, the elevated values observed in Sokoto and Jigawa demonstrate the additional influence of regional atmospheric processes. Thus, both anthropogenic activities and natural processes contribute to particulate pollution across the region, consistent with Ayua et al. (2020). Effective pollution management should therefore combine urban planning, control of industrial and transport emissions, reduction of biomass fuel dependence, and measures addressing regional dust transport.

Table 5: Population-Level Exposure Burden Among Vulnerable Groups

Vulnerable Group	Mean Exposure	PM _{2.5}	Relative Category	Risk
Children Under Five	45.1		Very High	
Elderly Population	42.8		High	
Pregnant Women	41.7		High	
Biomass Fuel Users	47.6		Extremely High	
Low-Income Households	44.3		Very High	

Table 5 shows that PM_{2.5} exposure is disproportionately concentrated among vulnerable population groups across Northwestern Nigeria. Biomass fuel users have the highest mean PM_{2.5} exposure (47.6 µg/m³) classified in the Extremely High relative risk category, followed by children under five years (45.1 µg/m³) and low-income households (44.3 µg/m³), both classified as Very High risk. The elderly population (42.8 µg/m³) and pregnant women (41.7 µg/m³) also experienced high exposure levels and were classified within the high-risk category. All groups were exposed to PM_{2.5} concentrations far exceeding international health guidelines, indicating widespread environmental health risks. These findings are consistent with previous studies showing that biomass fuel dependence, poverty, and physiological vulnerability significantly increase susceptibility to pollution-related respiratory diseases (Abubakar et al., 2025; Thacher et al., 2013). The results underscore the need for targeted interventions, including clean household energy, maternal and child health programmes, protection of older adults, and poverty reduction initiatives to reduce pollution exposure and associated health inequalities across Northwestern Nigeria.

Table 6: Major Atmospheric Pollution Exposure Hotspots

State	Dominant Exposure Characteristic
Kano	Severe particulate pollution
Kaduna	Industrial and traffic emissions
Sokoto	Dust aerosol accumulation

Katsina Biomass-combustion exposure

Table 6 identifies the major population exposure hotspots across Northwestern Nigeria based on the dominant characteristics of air pollution observed in each state. The results show that pollution exposure varies spatially, with states exhibiting distinct pollution profiles due to differences in land use, industrial activity, transportation, biomass combustion, and climatic conditions. These differences indicate that air quality management strategies should be tailored to each state's dominant pollution sources. Kano emerged as the major hotspot for severe particulate pollution, reflecting the combined influence of rapid urbanization, industrial activities, dense road traffic, commercial operations, and widespread biomass burning. Earlier findings from this study showed that Kano recorded the highest population-level exposure to PM_{2.5} (46.2 µg/m³), PM₁ (33.1 µg/m³), SO₂ (9.1 ppb), CO (1.42 ppm), O₃ (31.8 ppb), and AOD (0.89), confirming that residents experience the greatest overall pollution exposure. Pollution levels in Kano are high; Unah and Okopi (2021) identified Kano as one of Nigeria's most polluted urban centres due to industrial emissions, traffic congestion, and rapid population growth. Kaduna was identified as the hotspot for industrial and traffic-related emissions, reflecting its role as one of Northern Nigeria's major industrial centres. The state recorded relatively high concentrations of sulfur dioxide, carbon monoxide, and particulate pollutants, indicating substantial contributions from manufacturing industries, fossil fuel combustion, electricity generation, and vehicular emissions. Sokoto emerged as the principal hotspot for dust aerosol accumulation, largely due to its geographical location within the semi-arid Sahelian zone. The state experiences frequent Harmattan dust transport, desertification, wind erosion, and high atmospheric aerosol loading, which substantially increase population exposure to fine particulate matter. Earlier analyses in this study also identified Sokoto as having one of the highest PM_{2.5} concentrations, the highest pollution hotspot score, and the greatest respiratory disease burden. These findings agree with Georgakopoulou et al. (2024) who reported that northern Sahelian states experience persistent dust aerosol accumulation that significantly increases respiratory health risks. Katsina was identified as a biomass combustion exposure hotspot, reflecting extensive dependence on firewood, charcoal, agricultural residue burning, and other solid fuels for household energy. Biomass combustion generates large quantities of PM_{2.5}, carbon monoxide, and black carbon, increasing both indoor and outdoor air pollution. Katsina, as a biomass exposure hotspot, supports earlier findings of widespread biomass fuel use and elevated particulate pollution in the state. Similar observations were reported by Sani et al. (2025), who found that biomass fuel dependence remains a major driver of respiratory diseases in Northern Nigeria.

Table 7: Persistent Population Exposure Hotspots

State	Hotspot Persistence Level	Dominant Pollution Source
Kano	Very Persistent	Traffic and urban industrial emissions
Kaduna	Persistent	Industrial combustion
Sokoto	Very Persistent	Harmattan dust transport
Katsina	Persistent	Biomass combustion
Jigawa	Persistent	Harmattan dust transport and biomass combustion
Zamfara	Moderate	Aerosol transport
	Persistent	

Table 7 shows that Kano and Sokoto were the most persistent population exposure hotspots in Northwestern Nigeria. Kano was classified as Very Persistent, with its pollution burden mainly associated with traffic congestion, urbanisation, and industrial emissions; Sokoto was also Very Persistent, reflecting the strong influence of Harmattan dust transport and aerosol accumulation. Kaduna and Katsina were classified as persistent hotspots, with industrial combustion and biomass burning identified as their dominant pollution sources, respectively. Jigawa was also classified as a persistent hotspot, with Harmattan dust transport and biomass combustion identified as the dominant contributing sources. In contrast, Zamfara recorded a Moderately Persistent hotspot, largely associated with regional aerosol transport. These findings align with Abulude et al. (2024) who reported that industrial activities, traffic emissions, biomass combustion, and Harmattan dust contribute substantially to air pollution across Northern Nigeria. The results indicate that persistent population exposure hotspots occur where continuous anthropogenic emissions interact with recurring regional dust transport. This pattern supports developing state-specific pollution control strategies that target predominant sources within each state, aiming to reduce long-term population exposure and mitigate associated health risks.

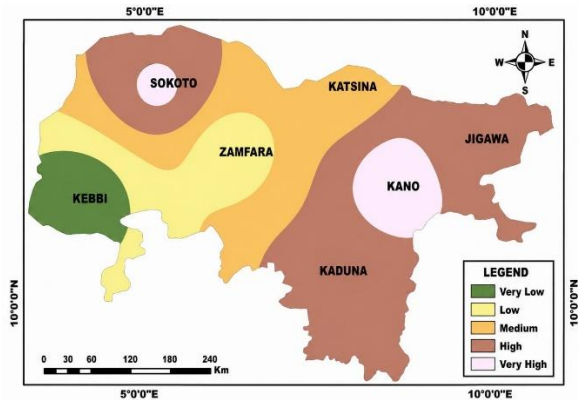


Figure 2: Composite Population Exposure Risk Index

Figure 2 shows the composite population exposure risk index across Northwestern Nigeria, with clear spatial differences in population exposure to atmospheric pollution. The map indicates

very high exposure in Kano and Sokoto, high exposure in Kaduna and Jigawa, Medium exposure in Katsina and Zamfara, and very low exposure in Kebbi. This spatial pattern indicates that population exposure varies across the region according to differences in pollutant concentrations, population distribution, and prevailing pollution sources. The Very High exposure recorded in Kano agrees with Idris et al. (2025), who reported elevated PM_{10} , $PM_{2.5}$, and $PM_{1.0}$ concentrations in Kano, supporting the high exposure identified in the present study. Similarly, the very high exposure in Sokoto agrees with Tariq et al. (2023), who reported substantial spatial and temporal variation in $PM_{2.5}$ during the Harmattan season in Sokoto State and identified wind as an important factor influencing particulate distribution. The High exposure recorded in Kaduna and Jigawa also reflects the broader pollution pattern reported for Northwestern Nigeria. Recent assessments have identified elevated particulate pollution across Kano, Jigawa, Katsina and Zamfara, with Saharan dust as a major contributor to $PM_{2.5}$ exposure in northern Nigeria (Moiwo et al., 2026).

Conclusion

This study shows that population exposure to atmospheric pollution across Northwestern Nigeria is driven by two interacting conditions: pollutant concentrations in the atmosphere and the number and characteristics of people living within those polluted environments—an assessment of $PM_{2.5}$, PM_{10} , SO_2 , CO , O_3 , and AOD shows that exposure is not distributed uniformly across the seven states. Instead, the region has distinct exposure zones: Kano and Sokoto are the principal high-exposure areas, Kaduna and Jigawa are important secondary exposure areas, and Kebbi consistently occupies the lower end of the regional exposure pattern. This spatial structure shows that atmospheric pollution in Northwestern Nigeria is a regional problem with strong state-specific characteristics rather than a uniform background condition. The study indicates that exposure factors vary by location. Kano represents a predominantly urban and anthropogenic exposure setting in which dense settlement, traffic, industrial activity, and fossil fuel combustion combine to sustain high particulate and gaseous pollution. Kaduna shows a similar connection between urban expansion, transportation, and industrial combustion. In Sokoto, however, high exposure occurs under a different environmental setting, where Harmattan dust and regional aerosol transport play a major role. Jigawa reflects the combined influence of dust transport and biomass combustion, while Katsina is strongly associated with biomass combustion. The implication is specific and important: reducing exposure in Kano and Kaduna requires stronger control of traffic, industrial, and fuel combustion emissions, whereas reducing exposure in Sokoto and Jigawa also requires measures that account for seasonal dust and regional aerosol transport. Biomass fuel reduction is particularly relevant to Katsina and other areas where household and agricultural combustion contributes to exposure. The population analysis further shows that high pollution becomes a more serious exposure concern where it coincides with high population concentration. Kano provides the clearest example, combining the highest population density with the highest population-weighted $PM_{2.5}$ exposure in the region. However, the exposure pattern in Sokoto and Jigawa indicates that population density alone is insufficient to explain variations in exposure. These states experience substantial particulate exposure despite having lower population densities than Kano and Kaduna. The regional exposure burden therefore results from the interaction of

population distribution with local emissions and atmospheric transport. These findings mean that pollution management based only on population density or on measured concentration would overlook important exposure locations.

The study also identifies a clear social dimension to the exposure burden. Biomass fuel users recorded the greatest PM_{2.5} exposure among the assessed population groups, while children under five and low-income households also experienced very high exposure. The elevated exposure among these groups links air pollution with household energy use and socioeconomic conditions. Consequently, air quality in Northwestern Nigeria cannot be limited to industrial and vehicular control. Substantial exposure reduction also requires greater access to cleaner household energy and interventions that reduce dependence on biomass fuels, particularly among households with limited economic capacity.

The persistence analysis provides further evidence that exposure in the region is not simply the result of occasional pollution events. Kano and Sokoto emerged as very persistent exposure hotspots, but for different reasons. Kano experiences ongoing pollution from traffic and industrial emissions, whereas Sokoto is persistently influenced by Harmattan dust transport. Kaduna, Katsina, and Jigawa also show persistent exposure associated with industrial combustion, biomass combustion, and the combined influence of dust and biomass burning. This distinction indicates that persistent exposure requires location-specific responses. Continuous emission reduction is vital in urban industrial hotspots, whereas seasonal dust preparedness, land management, and exposure mitigation are particularly vital in regions affected by recurring Harmattan conditions.

The application of machine learning adds methodological contribution to the study. The stronger results from ensemble models compared to linear regression show that simple linear relationships fail to capture population exposure. The superior performance of Extra Trees indicates that the exposure system contains interacting nonlinear relationships that are better represented when multiple environmental and pollution variables are considered together. Combined with the agreement between the gridded pollution estimates and ground observations, this supports integrated remote sensing, atmospheric modelling, and machine learning approaches for exposure assessment in areas where monitoring stations are insufficient.

The composite exposure assessment brings these dimensions together and identifies the most important intervention areas. Kano and Sokoto require attention, but their intervention needs are different. Kano requires stronger control of urban, traffic, and industrial emissions, while Sokoto requires greater attention to dust-related exposure and seasonal atmospheric transport. Kaduna and Jigawa require combined strategies addressing anthropogenic emissions and regional pollution processes, while Katsina requires particular attention to biomass combustion. The comparatively lower exposure observed in Kebbi does not remove the need for monitoring but indicates a lower immediate exposure priority relative to the other states.

This study shows that the major challenge for Northwestern Nigeria is not simply the presence of atmospheric pollutants, but the persistent intersection of pollution sources, atmospheric transport, population concentration and population vulnerability. The results provide a basis for moving from general statements about air pollution towards geographically targeted exposure management. Future air quality programmes in the region should therefore prioritise Kano and Sokoto as major exposure centres, strengthen

monitoring across persistent hotspots, reduce urban and industrial emissions where these dominate, expand access to cleaner household energy where biomass combustion is important, and incorporate seasonal dust conditions into exposure management. This integrated approach is a more appropriate basis for reducing population exposure across the seven states than a uniform regional pollution control strategy.

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