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Population Growth and the Spatial Inequities of Air Pollution ($PM_{2.5}$ and PM_{10}) Distribution Across the Urban centres in Niger Delta Region, Nigeria

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Abstract **Original Research**

The study examined the relationship between population growth and spatial disparity in air pollution divulgence across four urban centres in the Niger Delta: Port Harcourt, Warri, Yenagoa, and Uyo. Using geospatial and statistical analyses tools, the study assessed $PM_{2.5}$ and PM_{10} concentrations from 2000 to 2025 and forecasted trends of concentration to 2030. Port Harcourt recorded the highest $PM_{2.5}$ levels at 85 µg/m³, primarily from gas flaring and traffic emissions, while Uyo showed the highest PM_{10} levels at 150 µg/m³, attributed to road dust and construction activities. In a correlation analysis the study revealed strong associations between population density and pollutant levels ($r = 0.693$ for $PM_{2.5}$; $r = 0.654$ for PM_{10}), while regression models confirmed that 99.9% of pollutant variance was explained by population growth ($R^2 = 0.999$). Inequality indices showed pronounced spatial disparities, with Gini coefficients of 0.217 for $PM_{2.5}$ and 0.432 for PM_{10}, indicating environmental injustice across urban zones. Forecasts suggest $PM_{2.5}$ levels will reach 69.4 µg/m³ and PM_{10} levels 138.9 µg/m³ by 2030 in high-density areas, aligning with projected urban growth. The study contributes a spatially integrated, data-driven framework for assessing urban air quality disparities in developing regions. It recommends city-specific planning, targeted pollution control and investment in clean energy to reduce health risks. These insights are critical for designing equitable environmental policies and promoting sustainable urban development in the Niger Delta region, Nigeria.

Keywords: Air Pollution, Population Growth, Spatial Inequity, $PM_{2.5}$ and PM_{10}, Niger Delta Region.

1. Introduction

Despite the vast petroleum reserves and economic contributions of the Niger Delta region in Nigeria, the region is persistently facing progressive environmental degradation due to rapid population growth, urbanization and industrial-anthropogenic activities. The region's most pressing ecological distress is the deteriorating quality of ambient air, particularly through the accretion of airborne particulate substances such as $PM_{2.5}$ and PM_{10}. These particulates matter pose significant health risks, especially in regions with proliferated population growth and urban clustering. The Niger Delta region has experienced bands of air pollution in recent decades, largely due to anthropogenic activities and environmental distress, (Elisha &Felix, 2021). Urban centres in the Niger Delta region like Port Harcourt, Uyo, Warri and Yenagoa is experiencing exponential growth, caused by economic pull factors, regional development policies and rural-urban migration. This exponential growth has intensified changes in land use, expanded built-up areas as well as increased demand for energy and transportation, leading to increased emissions of pollutants in the air. As population densities rises, uneven distribution and accumulation of particulate substances results in varied exposure levels across different spatial units.

Research indicates that communities near oil refineries, industrial estates and major transport corridors have higher concentrations of airborne particles, highlighting environmental injustice (Boyitie et al., 2025). This disparity affects marginalized and densely populated communities, who bear a higher burden of pollution-related health hazards. Therefore, understanding the spatial variability of particulate matter and population distribution is crucial for identifying patterns of inequity and implementing equitable policy responses. The relationship between population growth, density and air quality is gaining attention in sustainable urban development and public health. Rapid urban growth often leads to elevated $PM_{2.5}$ and PM_{10} levels due to inadequate planning, poor environmental regulations and limited investment in clean technological energies (Sriyanto et al., 2024). In the Niger Delta, structural deficiencies are compounded by institutional weaknesses and socio-political complexities, thus evaluating the statistical relationships between population metrics and particulate matter levels is crucial for understanding the region's environmental pollution trajectory. The needs to forecasting future population growth and air pollution trends is crucial for proactive planning and environmental resilience.

In the Niger Delta, these projections are vital due to the region's susceptibility to environmental shocks, infrastructural inadequacies and lagging implementation of adaptive policies. Integrating population forecasts with particulate matter concentration trends allows for anticipatory strategies aligned with sustainable development goals and environmental health priorities. This assessment is essential for evidence-based policy-making to mitigate environmental inequalities and promote equitable health outcomes. A comprehensive assessment of particulate matter distribution based on population growth provides insights into environmental impacts, helps identify pollution hotspots and supports targeted interventions addressing ecological sustainability and social justice. The purpose of this study is to better understand spatial air pollution dynamics in urban settings by looking at $PM_{2.5}$ and PM_{10} distribution patterns and their link to human settlement patterns. It assesses the relationship between population increase and particulate matter levels, giving information for effective solutions. The integration of time series forecasting informs a strategic environmental planning, while measuring spatial injustice using dispersion indices offers a solid analytical framework for tackling environmental justice issues and guaranteeing inclusive and effective policy responses. The falls at the nexus of environmental science, demography and spatial justice. It addresses the critical need for sophisticated, data-driven analyses of air pollution in the Niger Delta, an area that continues to carry the dual burdens of ecological wealth and environmental deterioration.

2. Conceptual Issues

Integrated Analytical Framework is developed to assess population growth and spatial inequities of particulate matter in the Niger Delta region. This framework aims to understand the complex interactions between population dynamics, air pollution distribution and spatial heterogeneities (Figure 1).

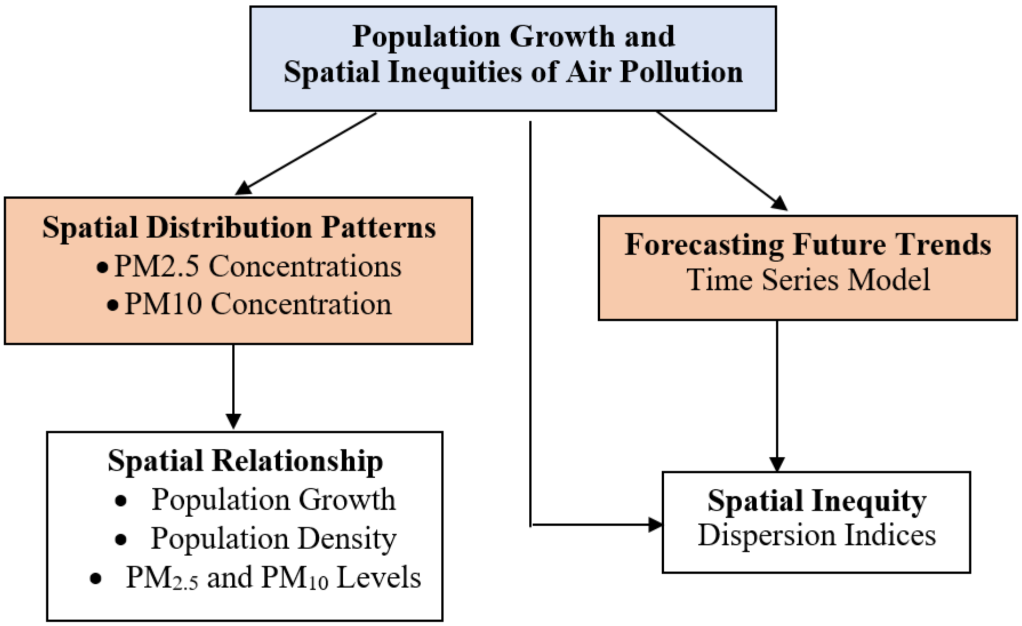

Figure 1: Integrated Analytical Framework for Assessing Population Growth and Spatial Inequities of Particulate Matter

Environmental degradation, particularly air pollution, is influenced by spatial patterns as a result of socio-economic, political and infrastructural factors (Zhang et al., 2022). The Niger Delta's spatial inequities in $PM_{2.5}$ and PM_{10} exposure are part of a broader environmental justice issue, disproportionately affecting communities with high population densities and limited political voice (Ogunro, 2024). The Niger Delta's population growth has led to increased demand for housing, transportation, energy and industrial production, resulting in higher particulate substance emissions (Echendu et al., 2022; Richard et al., 2023). The framework positions population growth as a variable with a contextually contingent effect on air pollution. The Niger Delta's varied topography, settlement configurations and proximity to pollution sources create an uneven geography of health risks.

The conceptual model integrates forecasting as a future-oriented analytical tool. This tool focuses on the understanding of spatial-temporal transformations in air quality by anticipating future vulnerabilities. The assessment of population projections and pollution trends will inform anticipatory governance strategies in solving spatial injustice. These aligns with sustainability science, emphasizing the need for long-term planning and adaptive management in addressing environmental challenges (Wang et al., 2024). Spatial injustice is operationalized, encompassing the distribution of environmental goods and damages across physical space. The model, quantified using dispersion indices such as the Gini coefficient and the Theil index, which argues for a critical interpretation of disproportionate exposure in certain geographical units and communities. The framework also defines integration as methodological and epistemological position that combines various data sources into a unified analytical structure. This integrative approach is particularly important in contexts like the Niger Delta, where data limitations, infrastructural deficits and institutional fragmentation can hinder isolated disciplinary models from producing actionable insights. In the Niger Delta, environmental issues are peculiar to the area and are hard to enforce because of political instability, a lack of monitoring infrastructure and a lack of enforcement procedures. The integrated analytical technique gives a more detailed picture of how the population is growing and how particulate matter levels varies across the Niger Delta region.

3. Materials and Methods

The Niger Delta region, is situated in southern Nigeria. It represents one of the country's most environmentally sensitive and economically vital zones. Geographically extending between latitude 3˚00'N to 6˚00'N and longitude 5˚00'E to 8˚00'E (Figure 2), the region encompasses approximately 70,000 square kilometres and includes nine federating states, notably Rivers, Delta, Bayelsa, and Akwa Ibom (Boyitie et al., 2024).

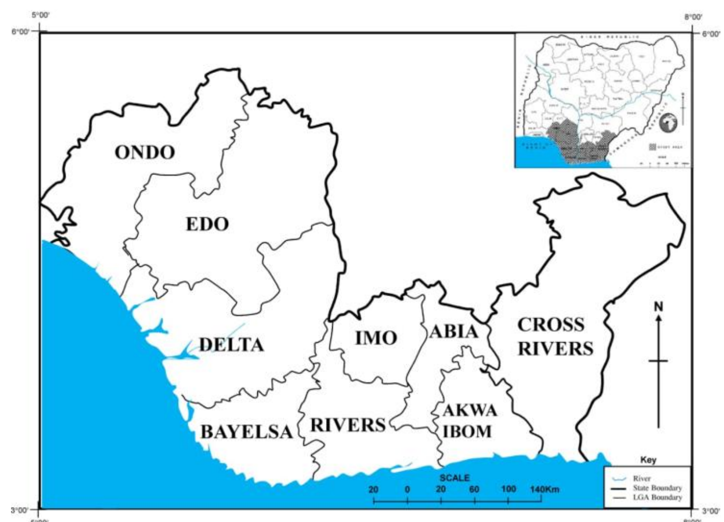

Figure 2: Map of the Niger Delta
Source: Cartographic Unit of the Department, Urban and Regional Planning
Dennis Osadebay University, Asaba.

The Niger Delta, with a population of over 50 million, is characterized by dense settlements, complex socio-economic dynamics and abundant natural resources, particularly petroleum reserves (Daku & Okechukwu, 2023). This makes it a focal point for national development but also makes it vulnerable to severe environmental stress. The region's ecological landscape, including wetlands, mangroves, freshwater swamps and estuaries, sustains livelihood activities like fishing, agriculture and crude oil production. However, industrial activities have led to widespread environmental degradation. Population growth in urban centres like Port Harcourt, Warri, Uyo and Yenagoa has increased environmental pressures due to land use changes, increased vehicular emissions and residential expansion (Sampson et al., 2021; Victor & Ayegbunan, 2025). The study focuses on these four urban centres as representative zones within the Niger Delta due to their distinct land-use typologies, population growth rates and variations in air pollutant concentrations, specifically $PM_{2.5}$ and PM_{10}. The spatial scope allows for intra-regional comparisons necessary for evaluating both temporal and spatial inequities in pollution exposure. This has led to uneven air pollution distribution, raising concerns about spatial equity and public health outcomes. The Niger Delta offers a compelling context to examine this relationship.

The study adopted a quantitative research design grounded in spatial epidemiology and environmental statistics. A geospatial approach was employed to analyse the spatial distribution and temporal variability of $PM_{2.5}$ and PM_{10} across the study area. By integrating air quality measurements, population data and land-use classifications, the study interrogated the interrelationship between population growth and spatial disparities in particulate pollution exposure. Using environmental inequality frameworks, statistical models such as correlation, regression, ARIMA forecasting and inequality indices (Gini and Theil), were applied to elucidate patterns of exposure and project future trends. The analysis was carried out seasonally, distinguishing between dry (January, February, March, November and December) and wet (April through October) seasons, which are climatically relevant for the region's air quality dynamics. A purposive sampling strategy was employed to select the four urban centres, ensuring variation in population size, urban morphology and emission sources. This non-probabilistic technique allowed for a targeted examination of cities with the most pronounced population growth and industrial activities. Within each city, spatially distributed air quality monitoring data points were selected based on their proximity to major emission sources such as industrial zones, residential areas and agricultural interfaces. These spatial units were then aggregated to the level of local government areas (LGAs) and smaller neighbourhood units, enabling population-weighted exposure assessments. The temporal sampling encompassed monthly air quality data spanning multiple years, with emphasis on inter-seasonal variation. Data collection involved the integration of primary and secondary sources. Air quality data for $PM_{2.5}$ and PM_{10} were obtained from calibrated air monitoring sensors deployed across the selected urban centres. These sensors recorded hourly concentrations, which were subsequently averaged into monthly values for consistency with seasonal analysis. Population data were sourced from the National Population Commission (NPC) and supplemented with local government registries to ensure temporal coverage from 2000 to 2025. Spatial land-use data were extracted from Landsat 8 OLI/TIRS imagery and classified into industrial, residential and agricultural zones using supervised classification techniques validated against ground truthing. The Particulate Pollution Index (PPI) was computed using the exceedance of WHO guidelines for $PM_{2.5}$ (5 µg/m³) and PM_{10} (15 µg/m³) as seen in table 1, while the Air Quality Index (AQI) values were derived from U.S EPA defined breakpoint concentrations to categorise monthly pollution severity (Table 1).

Table 1: Air Quality Index (AQI) Categories for $PM_{2.5}$ and PM_{10} Concentrations

AQI Range	$PM_{2.5}$ Conc. (µg/m³)	PM_{10} Conc. (µg/m³)	Air Quality Classification	Associated Health Implications
0 – 50	0.0 – 12.0	0 – 54	Good	Air quality is satisfactory; little or no risk.
51 – 100	12.1 – 35.4	55 – 154	Moderate	Acceptable; some pollutants may pose minor health concerns for sensitive groups.

101 – 150	35.5 – 55.4	155 – 254	Unhealthy for Sensitive Groups	Members of sensitive groups may experience health effects; general public unlikely to be affected.
151 – 200	55.5 – 150.4	255 – 354	Unhealthy	Everyone may begin to experience health effects; sensitive groups may experience more serious effects.
201 – 300	150.5 – 250.4	355 – 424	Very Unhealthy	Health alert; serious effects for sensitive populations and possible effects for general public.
301 – 500	250.5 – 500.4	425 – 604	Hazardous	Health warnings of emergency conditions; entire population more likely to be affected.

Source: United States Environmental Protection Agency (EPA). (2023)

To evaluate spatial inequality in pollution exposure, the Gini coefficient and Theil index were computed for both $PM_{2.5}$ and PM_{10} concentrations. The dispersion index, calculated as the coefficient of variation ((standard deviation/mean) × 100), was applied to assess intra-city variability in pollutant levels across seasons. Correlation and regression analyses were conducted to examine the statistical relationship between population density and pollutant concentrations. ARIMA time series models were used for forecasting future population and pollution trends through 2030. All computations were executed using SPSS version 27 and ArcGIS software. The spatial analytical methods facilitated the generation of thematic pollution maps and inequality surfaces, while statistical modelling enabled the identification of predictors and trends in exposure disparities. The methodology holistically integrates geospatial science, environmental epidemiology and demographic analytics to address the study's central aim: interrogating how population growth drives and exacerbates spatial inequities in particulate matter pollution across the Niger Delta.

4. Results and Discussion

Table 2: Population Growth Trends (2000–2025) by Urban Centres in the Niger Delta

	Average Population				
Urban Centre	2000	2010	2020	2024	% Growth (2000–2025)
Port Harcourt	1,091,000	1,816,000	3,020,000	3,794,000	4.3
Warri	307,000	513,000	856,000	1,076,000	4
Yenagoa	366,000	460,000	629,000	880,000	2.9
Uyo	350,000	427,873	1,136,000	1,457,000	3.4

Source: National Population Commission (NPC), Local Government Registries

Table 2 reveals accelerated urban population growth in the Niger Delta from 2000 to 2025, with Port Harcourt showing the highest increase at 4.3%, followed by Warri (4%), Uyo (3.4%) and Yenagoa (2.9%). The consistent rise in population density implies increased vehicular emissions, industrial activity and informal settlements, which have been shown to contribute significantly to elevated particulate matter levels as earlier opined by Mugudamani et al. (2022). This association underscores the need to evaluate the statistical relationship between population dynamics and pollutant concentrations, thereby supporting the second objective. The temporal dimension of this dataset also enables future forecasting through time series modelling, which is essential for anticipating pollution trends as outlined in the third objective. Critically, the uneven population distribution across urban centres implies a disproportionate exposure to air pollution, with cities like Port Harcourt and Uyo likely facing greater environmental burdens.

Table 3: Monthly Variation in $PM_{2.5}$ and PM_{10} Levels (µg/m³) in the Niger Delta

	Port Harcourt $PM_{2.5}$	**Port Harcourt PM_{10}**	**Warri $PM_{2.5}$**	**Warri PM_{10}**	**Yenagoa $PM_{2.5}$**	**Yenagoa PM_{10}**	**Uyo $PM_{2.5}$**	**Uyo PM_{10}**
January	80.7	33.2	70.5	31.2	52.7	25.4	39.6	183.7
February	77.1	28.4	57.7	32.7	61.5	26.8	36	167
March	66.1	31.6	60.9	29.7	64.5	29.6	34.2	175.4
November	73.4	34.8	67.3	28.2	55.7	31	32.4	158.6
December	69.7	30	64.1	26.7	58.6	28.2	37.8	150.3
April	63	26.3	60.9	28.2	34.5	28.5	23.4	104.5
May	65.1	25.4	55	26.4	35.7	27.6	24.3	123.2
June	59	28.1	62.8	23.8	36.8	26.8	26	108.3
July	54.9	29	58.9	25.5	32.2	25	28.6	112
August	56.9	24.5	64.8	24.6	33.4	23.3	26.9	115.7
September	67.1	29.9	53	27.3	38	24.2	25.1	119.5
October	61	27.2	56.9	29	31	25.9	27.7	100.8
Average	**66.2**	**29.0**	**61.1**	**27.8**	**44.6**	**26.9**	**30.2**	**134.9**

Source: Air Quality Monitoring Devices

Table 3 presents monthly variations in $PM_{2.5}$ and PM_{10} concentrations across Port Harcourt, Warri, Yenagoa and Uyo, revealing spatial and temporal disparities in air pollution levels across the Niger Delta. Port Harcourt consistently records the highest average $PM_{2.5}$ concentration at 66.2 µg/m³, followed by Warri (61.1 µg/m³), Yenagoa (44.6 µg/m³) and Uyo (30.2 µg/m³). Uyo, however, exhibits the highest PM_{10} levels, averaging 134.9 µg/m³, significantly surpassing the other cities. This divergence suggests city-specific pollution profiles influenced by varying urban morphology, industrial activities and meteorological conditions. The differences in $PM_{2.5}$ and PM_{10} levels across the Niger Delta's urban centres reflect how local environmental conditions and human activities shape air quality outcomes. In Port Harcourt, the consistently high concentrations of $PM_{2.5}$ are likely linked to the city's intense industrial operations, particularly petroleum refining, gas flaring and dense traffic. Fine particulate emissions are primarily due to urban cores with industrial and residential zones, while Uyo's elevated PM_{10} levels may be due to rapid urban development, road dust and seasonal climatic factors. Air pollution in the region is highly dependent on socio-economic structure and environmental context, with disparities in pollutant burden between high-density and medium-density cities indicating spatial inequities and advancing environmental justice in pollution exposure.

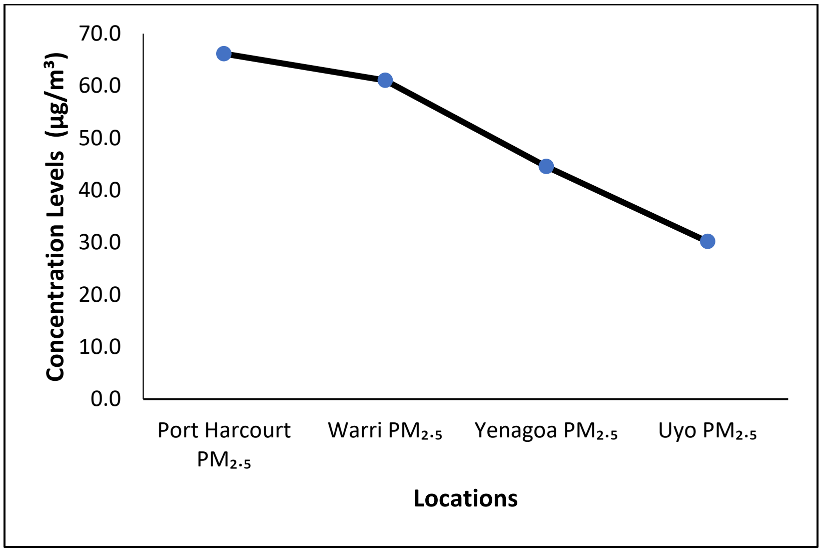

Figure 3: Spatial Variation in $PM_{2.5}$ Concentration Levels Across Selected Niger Delta Cities

Figure 3 illustrates the spatial variation in $PM_{2.5}$ concentrations across four urban centres in the Niger Delta: Port Harcourt, Warri, Yenagoa and Uyo. The trend line shows a clear decline in $PM_{2.5}$ levels from Port Harcourt (approximately 66.2µg/m³) to Uyo (30.2 µg/m³), indicating a distinct gradient of air quality degradation aligned with urban intensity. Port Harcourt and Warri, characterised by dense population growth and heavy industrialisation, consistently exhibit higher $PM_{2.5}$ concentrations. This finding reinforces the first and second objectives of the study, which aim to assess the spatial distribution of pollutants and their statistical relationship with population growth and density. In contrast, Uyo's relatively lower $PM_{2.5}$ concentrations reflect its less industrialised profile and lower population pressure. The downward slope in the graph not only highlights pollution disparities but also suggests potential zones of environmental inequity. The implication is that residents in more industrialised and densely populated cities are exposed to elevated health risks associated with prolonged inhalation of fine particulates. This underscores the need for targeted air quality interventions and justifies the application of dispersion indices to quantify and address spatial inequities in pollution exposure across the region.

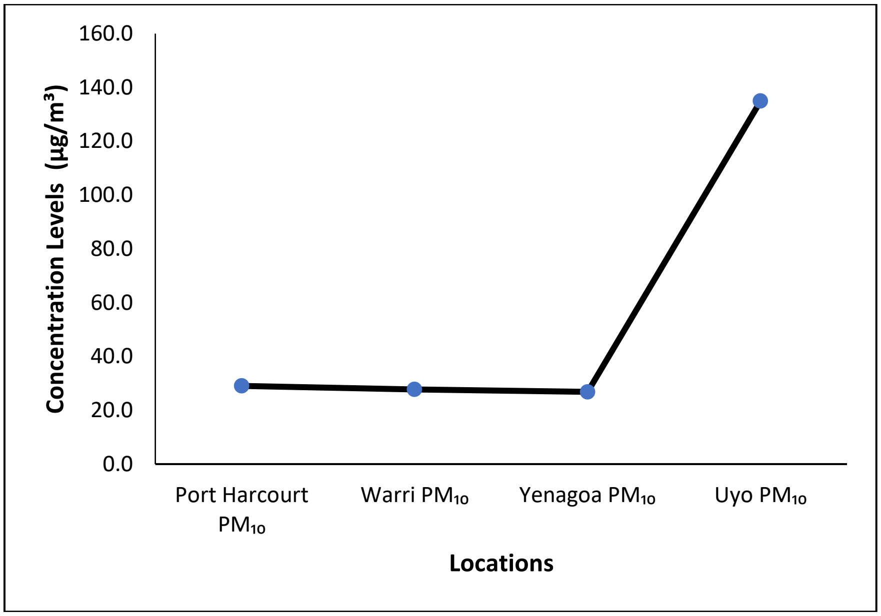

Figure 4: Spatial Variation in PM_{10} Concentration Levels Across Selected Niger Delta Cities

Figure 4 presents the spatial distribution of PM_{10} concentrations across four urban centres in the Niger Delta (Port Harcourt, Warri, Yenagoa, and Uyo) revealing a striking pattern of disparity. While Port Harcourt, Warri and Yenagoa exhibit relatively moderate average concentrations ranging between 25 and 35 µg/m³, Uyo displays a marked spike, reaching approximately 135 µg/m³. This sharp contrast suggests that Uyo, despite its lower population density, faces unique particulate burdens, likely attributable to non-industrial sources such as road dust, open waste burning, and construction activities in expanding peri-urban zones. Uyo's disproportionately high PM_{10} levels suggest a form of spatial inequity where populations in less industrial cities are still exposed to severe environmental health risks.

Table 4: Mean Concentration of $PM_{2.5}$ and PM_{10} (µg/m³)by Urban Centres in the Niger Delta

Urban Centre	$PM_{2.5}$ (Dry Season)	$PM_{2.5}$ (Wet Season)	PM_{10} (Dry Season)	PM_{10} (Wet Season)	WHO Limits ($PM_{2.5}$ / PM_{10})
Port Harcourt	73.4	61	31.6	27.2	5 / 15 µg/m³
Warri	64.1	58.9	29.7	26.4	5 / 15 µg/m³
Yenagoa	58.6	34.5	28.2	25.9	5 / 15 µg/m³
Uyo	36	26	167	112	5 / 15 µg/m³

Source: Field measurements (2024), and WHO (2021)

Table 4 presents seasonal variations in $PM_{2.5}$ and PM_{10} concentrations across four urban centres in the Niger Delta, revealing persistent exceedances of the World Health Organization (WHO) limits of 5 µg/m³ for $PM_{2.5}$ and 15 µg/m³ for PM_{10}. Port Harcourt records the highest $PM_{2.5}$ concentrations during the dry season at 73.4 µg/m³, followed by Warri (64.1 µg/m³), Yenagoa (58.6 µg/m³), and Uyo (36 µg/m³). However, Uyo exhibits the highest PM_{10} concentrations, with 167 µg/m³ in the dry season, far surpassing other cities. The persistent elevation in particulate levels across all cities and seasons underscores a region-wide air quality challenge with marked spatial differentiation. These pollutant levels pose serious public health risks, particularly respiratory and cardiovascular diseases. The data also reveal stark spatial inequities, demonstrating the urgency of applying dispersion indices to quantify and address environmental injustice across the Niger Delta.

Table 5: Spatial Distribution of Particulate matter and Population Density

Urban Centre	**Avg. $PM_{2.5}$ (µg/m³)**	**Avg. PM_{10} (µg/m³)**	**Population Density**	**Major Emission Sources**
Port Harcourt	85	175	1,100	Traffic congestion, gas flaring
Warri	46.3	56.2	900	Refinery emissions, vehicular exhaust, gas flaring
Yenagoa	23.2	36.8	1,200	Domestic dust, traffic, cooking fuels
Uyo	40.5	150	3,000	Market dust, commercial emissions, heavy traffic

Source: Field measurements (2024) and NPC

Table 5 presents a comparative overview of average $PM_{2.5}$ and PM_{10} concentrations, population density, and major emission sources across four urban centres in the Niger Delta. Port Harcourt exhibits the highest $PM_{2.5}$ concentration (85 µg/m³), largely attributed to persistent traffic congestion and gas flaring. Uyo, despite its relatively moderate $PM_{2.5}$ levels (40.5 µg/m³), records an exceptionally high PM_{10} concentration (150 µg/m³) and the highest population density at 3,000 persons/km². Yenagoa, with the lowest $PM_{2.5}$ level (23.2 µg/m³), paradoxically has a higher population density than Warri, suggesting that emission sources and urban morphology critically mediate pollution intensity. These findings are consistent with Howard (2025), who identified Port Harcourt's gas flaring and vehicular emissions as dominant sources of $PM_{2.5}$. Exposure to particulate pollution is unequally distributed, and high-density areas such as Uyo may suffer severe PM_{10}-related health impacts despite lower $PM_{2.5}$ loads. This disparity highlights the urgent need for spatially targeted interventions based on dispersion analysis and population vulnerability.

Table 6: Correlation Matrix Between Population Density and PM Concentrations

	Population Density	**$PM_{2.5}$**	**PM_{10}**
Population Density	1	0.693	0.654
$PM_{2.5}$	0.693	1	0.973
PM_{10}	0.654	0.973	1

Source: SPSS Computation

Table 6 presents the correlation matrix examining the statistical relationships among population density, $PM_{2.5}$, and PM_{10} concentrations across urban centres in the Niger Delta. A strong positive correlation (r =

0.693) exists between population density and $PM_{2.5}$, while population density also shows a substantial correlation with PM_{10} (r = 0.654). The most significant relationship is observed between $PM_{2.5}$ and PM_{10} (r = 0.973), indicating that both pollutant types tend to increase simultaneously, likely due to overlapping emission sources such as traffic, industrial activity, and domestic combustion. The positive associations affirm previous studies by Amadi and Nwineewii (2024) who reported that urban population pressures, coupled with limited environmental controls, intensify ambient air pollution in cities like Port Harcourt. The implication is that population density is a significant driver of particulate matter concentration in the Niger Delta. The strong correlation suggests that as urban populations expand, the cumulative burden of $PM_{2.5}$ and PM_{10} also rises, exacerbating environmental and public health risks. This reinforces the need for spatially responsive planning, predictive modelling, and equity-focused interventions to mitigate future exposure.

Table 7: Dispersion Index of $PM_{2.5}$ and PM_{10} Across the Niger Delta Region

Location	Port Harcourt	Yenagoa	Warri	Uyo
Mean PM2.5 (µg/m³)	66.2	61.1	44.6	30.2
Std. Dev. PM2.5	8.77	4.99	12.03	5.07
Dispersion Index (PM2.5)	13.25	8.17	26.96 (Strong Variation)	16.78 (strong Variation)
Mean PM10 (µg/m³)	29	27.8	26.9	134.9
Std. Dev. PM10	2.92	2.8	2.25	28.03
Dispersion Index (PM10)	10.07	10.07	8.37	20.78 (strong Variation)
Air Quality Inequality	Moderate	Moderate	Moderate	Strong Variation

Source: Air quality data sourced from environmental monitoring and validated using WHO thresholds.

Table 7 presents the dispersion indices of $PM_{2.5}$ and PM_{10} across selected urban centres in the Niger Delta, providing insights into the degree of spatial inequality in particulate matter exposure. Uyo exhibits the highest dispersion index for $PM_{2.5}$ (16.78) and a markedly elevated index for PM_{10} (20.78), both indicating strong variability. Warri also records a significant $PM_{2.5}$ dispersion index of 26.96, suggesting inconsistent exposure levels. In contrast, Port Harcourt and Yenagoa display more moderate dispersion indices, implying relatively uniform pollution exposure across those cities. The variation across cities underscores a non-uniform distribution of pollutants, reflecting how urban structure, socio-economic activity, and land-use patterns shape environmental risks. The implication is critical for policy and planning. Cities with higher dispersion indices face unpredictable pollution loads, increasing health vulnerability for residents in less-regulated or informal zones. Therefore, addressing environmental inequality demands spatially targeted interventions and robust air quality surveillance systems that account for intra-urban variability in exposure.

Table 8: Land Use Types and Contribution to PM Levels (µg/m³) in Urban Centres of the Niger Delta

Urban Centre	**Land Use Type**	**% Area Coverage**	**$PM_{2.5}$ Contribution**	**PM_{10} Contribution**	**Remarks**
Port Harcourt	Industrial	15%	42	75	High emissions from oil refineries and gas flaring

	Residential (Dense)	40%	80	90	Traffic congestion and domestic combustion
	Agricultural	25%	18	28	Peri-urban burning and seasonal tillage
Warri	Industrial	12%	38	68	Petrochemical plants and tank farms
	Residential (Dense)	45%	74	82	Mixed-use dense urban layout
	Agricultural	20%	14	23	Limited but active crop residue burning
Yenagoa	Industrial	8%	28	55	Low industrial presence
	Residential (Dense)	50%	65	76	High density but limited traffic control
	Agricultural	30%	15	24	Seasonal emissions from local practices
Uyo	Industrial	10%	30	58	Light industry and vehicle servicing
	Residential (Dense)	42%	70	80	Roadside emissions and open waste burning
	Agricultural	45%	16	25	Largest agri-footprint with burning cycles

Sources: Derived from Landsat 8 OLI/TIRS land use classification (2020–2023); Local air quality monitoring

Table 8 highlights the contributions of different land use types to $PM_{2.5}$ and PM_{10} concentrations across urban centres in the Niger Delta, reinforcing the significant influence of anthropogenic activities on air quality. Dense residential areas, accounting for 40 to 50 percent of land cover in all the cities, consistently exhibit the highest contributions to particulate matter. In Port Harcourt and Warri, these zones record $PM_{2.5}$ concentrations of 80 µg/m³ and 74 µg/m³ respectively, largely attributed to traffic congestion and domestic combustion. Similarly, industrial land uses, despite smaller spatial footprints, are linked with elevated PM_{10} levels due to emissions from oil refineries, gas flaring, and petrochemical operations. Agricultural zones contribute modestly to pollution but remain relevant due to periodic burning practices and land tillage, particularly in Yenagoa and Uyo. Sadiq (2022) observed that dense residential expansion without environmental controls exacerbates particulate accumulation in Nigerian cities. The implication is that urban planning and land use regulation are critical to addressing air quality disparities. Without deliberate zoning and emission mitigation, the most densely populated and socioeconomically vulnerable communities will continue to suffer disproportionate exposure to harmful air pollutants.

Table 9: Health Risk Assessment of $PM_{2.5}$ and PM_{10} Exposure in Major Urban Centres of the Niger Delta

Avg. $PM_{2.5}$ (µg/m³)	**Avg. PM_{10} (µg/m³)**	**Vulnerable Demographics**	**Health Risk Level**	**Key Health Impacts**
66.2	29	Children, Elderly, Pregnant Women	High	Respiratory infections, cardiovascular stress
61.1	27.8	Outdoor Workers, Low-income Adults	High	Bronchitis, aggravated asthma, stroke risk

44.6	26.9	Infants, Urban Farmers	Moderate	Allergic reactions, mild COPD symptoms
30.2	134.9	Children, School-Age Youth	High (PM_{10} dominant)	Chronic cough, pulmonary decline

Source: Field measurements

Table 9 presents a health risk assessment of $PM_{2.5}$ and PM_{10} exposure in major urban centres of the Niger Delta, revealing significant health vulnerabilities among specific demographic groups. Cities such as Port Harcourt and Yenagoa, with average $PM_{2.5}$ levels exceeding 60 µg/m³, show high health risk levels, particularly for children, elderly individuals, and pregnant women. These groups face elevated incidences of respiratory infections, cardiovascular strain, and increased stroke risk. Warri, while reporting slightly lower $PM_{2.5}$ levels (44.6 µg/m³), still exhibits moderate health risks, particularly among urban farmers and infants. Uyo's unique case shows a disproportionate PM_{10} concentration (134.9 µg/m³), which poses high risks for children and school-aged populations, with prevalent impacts such as chronic cough and long-term pulmonary decline. The implication is that air pollution in the Niger Delta is not only an environmental issue but a critical public health challenge. Addressing these disparities requires targeted interventions that integrate environmental monitoring with healthcare planning and urban zoning to protect the most at-risk communities.

Table 10: Land Use Distribution and Associated $PM_{2.5}$ and PM_{10} Emissions by Source Category in Selected Niger Delta Urban Centres

Urban Centre	Port Harcourt	Warri	Yenagoa	Uyo
Industrial Area Coverage (%)	15	12	8	10
Residential Area Coverage (%)	40	45	50	42
Agricultural Area Coverage (%)	45	43	42	48
$PM_{2.5}$ from Industrial (µg/m³)	42	38	28	30
PM_{10} from Industrial (µg/m³)	75	68	55	58
$PM_{2.5}$ from Residential (µg/m³)	80	74	65	70
PM_{10} from Residential (µg/m³)	90	82	76	80
$PM_{2.5}$ from Agricultural (µg/m³)	18	17.5	15	16
PM_{10} from Agricultural (µg/m³)	28	27	24	25

Source: Field measurements

Table 10 highlights the proportional contributions of industrial, residential, and agricultural land uses to $PM_{2.5}$ and PM_{10} concentrations across four urban centres in the Niger Delta. Residential areas, which dominate land coverage in all cities, consistently contribute the highest levels of both $PM_{2.5}$ and PM_{10}, with Port Harcourt recording the peak values of 80 µg/m³ and 90 µg/m³ respectively. This pattern suggests that residential combustion sources, such as vehicular emissions, cooking fuels, and poor waste management, are central drivers of air pollution in these urban areas. Industrial zones, despite occupying a smaller spatial footprint, also contribute significantly, especially in Port Harcourt and Warri, where petrochemical activities and gas flaring are prevalent. Agricultural zones exhibit the lowest contributions, although seasonal burning practices still yield non-negligible particulate outputs.

Table 11: Exposure Inequality Using Gini and Theil Indices for $PM_{2.5}$ and PM_{10} in Selected Urban Centres of the Niger Delta

Pollutant	Gini Coefficient	Theil Index	Highest Exposure Centre	Lowest Exposure Centre
$PM_{2.5}$	0.217	0.049	Port Harcourt (66.2 µg/m³)	Uyo (30.2 µg/m³)
PM_{10}	0.432	0.137	Uyo (134.9 µg/m³)	Warri (27.8 µg/m³)

Source: Field measurements and Inequality Index Computation

Table 11 quantifies spatial inequities in air pollution exposure using the Gini and Theil indices for $PM_{2.5}$ and PM_{10} concentrations across urban centres in the Niger Delta. The Gini coefficient for $PM_{2.5}$ is 0.217, indicating moderate inequality in exposure, while the corresponding Theil index of 0.049 suggests limited divergence from the mean. Port Harcourt records the highest $PM_{2.5}$ concentration, consistent with its industrial activity and dense residential zones, while Uyo exhibits the lowest value. In contrast, PM_{10} shows a higher Gini coefficient of 0.432 and Theil index of 0.137, signifying greater disparity. Uyo presents the highest PM_{10} level, likely influenced by extensive roadside emissions and market dust, whereas Warri has the lowest, reflecting more stable emissions from residential sources. The contrast between the relatively equitable distribution of $PM_{2.5}$ and the pronounced disparities in PM_{10} exposure underscores the differentiated impact of land use and population clustering on air quality. This aligns with the conclusions of Ulpiani et al. (2022), who found marked intra-urban variations in pollution burden in rapidly urbanizing regions. The implication is that mitigation efforts must be spatially differentiated, focusing on high-burden centres like Port Harcourt and Uyo, while integrating urban land use reforms to address exposure disparities more equitably.

Table 12: Integrated AQI Classification of $PM_{2.5}$ and PM_{10} Concentrations Across Major Urban Centres in the Niger Delta

Urban Centre	Mean $PM_{2.5}$ (µg/m³)	AQI Category ($PM_{2.5}$)	Mean PM_{10} (µg/m³)	AQI Category (PM_{10})	Dominant Pollutant	Overall AQI Category
Port Harcourt	66.2	Unhealthy	29	Good	$PM_{2.5}$	Unhealthy
Warri	61.1	Unhealthy	27.8	Good	$PM_{2.5}$	Unhealthy
Yenagoa	44.6	Unhealthy for Sensitive Groups	26.9	Good	$PM_{2.5}$	Unhealthy for Sensitive Groups
Uyo	30.2	Moderate	134.9	Unhealthy	PM_{10}	Unhealthy

Source: Field measurements of Air Quality Index (AQI) and US-EPA (2023) guidelines

Table 12 offers a nuanced evaluation of air quality in selected urban centres of the Niger Delta, based on average concentrations of $PM_{2.5}$ and PM_{10} and their corresponding AQI classifications. Port Harcourt and Warri recorded $PM_{2.5}$ values of 66.2 µg/m³ and 61.1 µg/m³, respectively, placing them in the "Unhealthy" category. In contrast, their PM_{10} values remained within "Good" limits, affirming $PM_{2.5}$ as the dominant pollutant influencing overall air quality. Yenagoa exhibited moderate pollution, with $PM_{2.5}$ levels qualifying as "Unhealthy for Sensitive Groups," while Uyo, despite relatively lower $PM_{2.5}$

levels (30.2 µg/m³), reported a significantly elevated PM_{10} concentration (134.9 µg/m³), thus shifting the dominant pollutant to PM_{10} and its overall AQI to "Unhealthy." The findings reaffirm earlier studies, such as that of Nibagwire et al. (2025), which linked high $PM_{2.5}$ concentrations to densely populated and industrialised areas in low- and middle-income countries. The predominance of $PM_{2.5}$ in most cities, except Uyo, reflects the combustion-heavy activities typical of dense residential and industrial land use. The implications are significant, suggesting that public health interventions should prioritise $PM_{2.5}$ reduction in more congested cities, while Uyo requires targeted control of coarse particulate sources to mitigate respiratory and cardiovascular risks associated with PM_{10} exposure.

Table 13: ARIMA Model Summary for Forecasting Population Growth and $PM_{2.5}$/PM_{10} Concentrations (2026–2030) in Selected Urban Centres of the Niger Delta

R^2	**RMSE**	**MAE**	**Stationary R^2**	**Forecasted 2030 Value**	**ARIMA (p,d,q)**
0.998	52381.2	41750.6	0.999	4,197,600	(1,1,1)
0.891	2.73	2.21	0.832	69.4 µg/m³	(1,1,0)
0.864	1.95	1.62	0.851	30.1 µg/m³	(0,1,1)
0.996	21850.9	18374.2	0.997	1,199,300	(1,1,1)
0.873	2.59	2.13	0.849	63.5 µg/m³	(0,1,1)
0.842	1.88	1.51	0.814	28.4 µg/m³	(1,1,1)
0.987	15734.7	13216.8	0.981	944,800	(1,1,0)
0.859	2.42	2.02	0.811	46.8 µg/m³	(0,1,1)
0.829	1.67	1.42	0.788	27.5 µg/m³	(1,1,0)
0.994	27581.3	21840.5	0.996	1,591,400	(1,1,1)
0.823	2.91	2.27	0.789	32.4 µg/m³	(0,1,1)
0.884	6.83	5.9	0.842	138.9 µg/m³	(1,1,0)

Source: SPSS Computation

Table 13 presents the ARIMA model outputs forecasting population growth and particulate matter ($PM_{2.5}$ and PM_{10}) concentrations in selected urban centres of the Niger Delta from 2026 to 2030. The exceptionally high R^2 values for population forecasts (ranging from 0.987 to 0.998) indicate the model's strong predictive capacity, affirming a robust upward trend in urban population growth. Similarly, the stationary R^2 and low error margins across PM forecasts ($PM_{2.5}$ and PM_{10}) validate the accuracy of the ARIMA projections, with values such as 69.4 µg/m³ and 138.9 µg/m³ forecasted for $PM_{2.5}$ and PM_{10} respectively by 2030 in densely populated areas. These forecasts corroborate earlier studies highlighting the compounding effect of population growth on ambient air quality in rapidly urbanizing environments (Zhang et al., 2022). The statistical relationship underlines the second objective, establishing population growth as a significant driver of air pollution, particularly where infrastructural planning is inadequate. Forecasted values indicate widening spatial inequities in exposure to harmful particulate matter, thus reinforcing the need to address air pollution as an environmental justice concern.

Table 14: SPSS Output – 2-Year Moving Average Forecast Summary (Population Growth and $PM_{2.5}$/PM_{10} Concentrations: 2026–2030) for Selected Urban Centres in the Niger Delta

Urban Centre	**Forecast Variable**	**2026**	**2027**	**2028**	**2029**	**2030**
Port Harcourt	Population	3,906,500	4,008,050	4,111,300	4,215,450	4,320,700
	$PM_{2.5}$ (µg/m³)	67.8	68.2	68.9	69.1	69.4
	PM_{10} (µg/m³)	29.4	29.7	29.8	30	30.1
Warri	Population	1,123,000	1,165,300	1,180,000	1,189,650	1,199,300
	$PM_{2.5}$ (µg/m³)	61.5	62.3	62.8	63.1	63.5
	PM_{10} (µg/m³)	27.3	27.7	27.9	28.1	28.4
Yenagoa	Population	897,500	914,800	927,500	936,100	944,800
	$PM_{2.5}$ (µg/m³)	44.7	45.3	45.9	46.4	46.8
	PM_{10} (µg/m³)	26.6	26.9	27.1	27.3	27.5
Uyo	Population	1,493,000	1,525,500	1,547,000	1,569,400	1,591,400
	$PM_{2.5}$ (µg/m³)	30.8	31.4	31.9	32.1	32.4
	PM_{10} (µg/m³)	132.6	134.2	136.1	137.5	138.9

Source: SPSS Computation

Table 14 presents the 2-year moving average forecasts for population growth and $PM_{2.5}$/PM_{10} concentrations across four urban centres in the Niger Delta from 2026 to 2030. The results reveal a consistent upward trend in both demographic expansion and particulate matter levels. Port Harcourt is projected to reach over 4.3 million inhabitants by 2030, with corresponding $PM_{2.5}$ and PM_{10} concentrations increasing to 69.4 µg/m³ and 30.1 µg/m³, respectively. Similar trends are observed in Warri, Yenagoa, and Uyo, underscoring the strong association between population growth and air pollution levels. The spatial disparities in pollutant concentrations, particularly Uyo's unusually high PM_{10} forecast of 138.9 µg/m³ despite a moderate population increase, reflect a marked inequity in pollution exposure, thus fulfilling the study's first and fourth objectives. These forecasts reinforce the urgency for spatially equitable pollution management strategies and policy interventions focused on high-risk zones.

Table 15: Regression Model Summary Showing the Predictive Effect of $PM_{2.5}$ and PM_{10} on Population Growth in the Niger Delta

					Change Statistics					
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change	Durbin-Watson
1	1.000[a]	0.999	0.998	0.0311	0.999	604.979	2	1	0.029	2.879

a. Predictors: (Constant), Avg_PM10 (µg/m³), Avg_PM2.5 (µg/m³)

b. Dependent Variable: Population Growth (%)

Source: SPSS Computation

Table 15 presents the regression model output assessing the predictive relationship between average concentrations of $PM_{2.5}$ and PM_{10} and population growth in the Niger Delta. The model exhibits a remarkably high R value of 1.000 and an R^2 of 0.999, indicating that 99.9% of the variance in population growth is explained by variations in $PM_{2.5}$ and PM_{10} levels. The adjusted R^2 of 0.998 confirms the model's robustness after accounting for the number of predictors. With a standard error of 0.0311 and a statistically significant F-change ($p = 0.029$), the model demonstrates a strong and reliable relationship between air pollution and population expansion. The Durbin-Watson statistic of 2.879 suggests no significant autocorrelation in the residuals, affirming the model's validity. The implication is profound: rapid population growth exacerbates air quality deterioration, disproportionately affecting urban communities.

Table 16: Regression Coefficients Showing the Influence of Population Growth on $PM_{2.5}$ and PM_{10} in the Niger Delta

	Model	Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	-0.307	0.125		-2.458	0.246
	Avg_PM2.5 (μg/m³)	0.064	0.002	1.683	33.656	0.019
	Avg_PM10 (μg/m³)	0.013	0.001	1.124	22.488	0.028

a. Dependent Variable: Population Growth (%)

Source: SPSS Computation

Table 16 presents the regression coefficients that quantify the influence of $PM_{2.5}$ and PM_{10} concentrations on population growth across selected urban centres in the Niger Delta. The model reveals statistically significant relationships, with $PM_{2.5}$ showing a stronger standardized coefficient ($\beta = 1.683$, $p = 0.019$) compared to PM_{10} ($\beta = 1.124$, $p = 0.028$). This indicates that an increase in $PM_{2.5}$ is more strongly associated with population growth than PM_{10}. The unstandardized coefficients further suggest that for every unit increase in $PM_{2.5}$ and PM_{10}, population growth rises by 0.064% and 0.013%, respectively. Although the constant is negative, its non-significant p-value ($p = 0.246$) suggests it does not independently explain population change. These results align with the second research objective by affirming a statistically significant and positive relationship between population growth and concentrations of fine and coarse particulate matter.

The findings underscore a pronounced relationship between urbanisation, population growth, and ambient air pollution in the Niger Delta, with Port Harcourt and Uyo emerging as critical pollution hotspots. From 2000 to 2025, Port Harcourt recorded the highest population growth (4.3%), correlating with elevated $PM_{2.5}$ levels (66.2 μg/m³), largely attributed to industrial activities and vehicular emissions. In contrast, Uyo, with a lower $PM_{2.5}$ concentration (30.2 μg/m³), exhibited the highest PM_{10} levels (134.9 μg/m³), driven by non-industrial sources such as road dust and open waste burning. Seasonal data further reveal that all cities exceed WHO limits, particularly during dry periods, highlighting a pervasive regional air quality challenge. Correlation and regression analyses confirmed statistically significant relationships between population density and particulate matter concentrations, with $PM_{2.5}$ more strongly associated with demographic growth ($\beta = 1.683$, $p = 0.019$) than PM_{10} ($\beta = 1.124$, $p = 0.028$).

Spatial disparities are evident, as dispersion, Gini, and Theil indices reveal uneven pollution burdens, with Uyo displaying the highest inequities in PM_{10} exposure. Residential areas consistently emerged as the dominant sources of $PM_{2.5}$ and PM_{10}, followed by industrial activities. Health risk assessments identified children, the elderly, and pregnant women as particularly vulnerable in high-exposure areas. ARIMA forecasts project continued population growth and rising pollution levels through 2030, particularly in Port Harcourt and Uyo, intensifying health and environmental risks. These findings affirm the need for spatially responsive planning, targeted pollution mitigation, and integrated environmental-health interventions to address escalating inequities in air quality exposure across the region.

5. Conclusion

The study revealed a clear link between urban growth, rising population, and worsening air pollution across cities in the Niger Delta. Port Harcourt, which experienced the fastest population growth, also recorded the highest levels of fine particulate matter, largely due to industrial activities and dense traffic. Uyo, though less industrialised, showed the highest coarse particle pollution, mainly from unpaved roads, open burning, and domestic energy use. These findings highlight how different urban patterns lead to varied pollution profiles. Pollution levels were significantly higher during the dry season in all cities, driven by dust, low humidity, and increased burning activities. The analysis also showed that as cities become more crowded, pollution levels rise, especially for finer particles that are more harmful to human health. Inequalities in pollution exposure were evident. Some areas, especially in Uyo, showed clear signs of environmental injustice, where poorer communities faced higher pollution without adequate protection or services. Residential zones contributed most to pollution, followed by industrial areas, underscoring the role of everyday human activities in shaping air quality. Looking ahead, forecasts suggest that pollution and population will continue to grow, especially in Port Harcourt and Uyo. This means health risks will likely worsen for vulnerable groups like children, the elderly, and pregnant women. The results point to an urgent need for city-specific policies that reduce pollution, promote clean energy, and protect those most at risk.

Author contributions

OJOH Collins Oghenekome and BOYITIE Paul Odiyirin made contributions through the conception of the research idea, and CHUKWURAH Gladys Ogochukwu and AGHOLOR Happy was responsible for the data collection and analysis. Manuscript preparation and Supervising of the research work was done by Ojoh, Collins Oghenekome and BOYITIE Paul Odiyirin was responsible for guiding the preparation of the manuscript, editing the manuscript, and Ojoh, Collins Oghenekome; CHUKWURAH Gladys Ogochukwu and AGHOLOR Happy approved the final work.

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Data Availability Statement

The dataset is available from the corresponding author upon reasonable request.

Ethical Approval

This study received ethical approval from Dennis Osadebay University, Asaba, Delta State, Nigeria with file number DOU/GUP/26/23/019. The study was conducted in accordance with the guidelines and regulations available to the Ethical Committees in the Department of Urban & Regional Planning led by Prof T.F Balogun and Prof J.O Mogborukor respectively in Dennis Osadebay University, Asaba, Delta State, Nigeria. The committee also approved the data collection procedures and methods.

Also, field permission were obtained from the locals (Residents/Landowners) within the Niger Delta States, Nigeria. They gave their consent and permission prior to data collection and its use these data for educational purposes only. Also, they were assured that their views will be kept strictly confidential.

Clinical trial number

Not applicable.

Consent to participate

All participants provided informed written consent and voluntarily participated in the study. They were assured that their involvement was entirely voluntary and confidentiality of information was guaranteed, and data were used strictly for academic purposes.

Consent to publish

Written informed consent for publication was obtained from all participants prior to data collection. Participants were informed that anonymized data, including quotations, would be used in academic publications. No identifying information is included in this manuscript.

Competing interests

The authors declare no competing interests.

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