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Assessment of Black Carbon (Soot) Pollution and Its Impact on Ambient Air Quality in Port Harcourt Metropolis, Rivers State, Nigeria

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Abstract

Air pollution associated with black soot has become a major environmental and public health concern in Port Harcourt, Rivers State, Nigeria. This study assessed the concentrations of black carbon (BC) and particulate matter ($PM_{2.5}$ and PM_{10}) and their impact on ambient air quality across selected locations in the metropolis. A cross-sectional sampling design was adopted, covering both dry and wet seasons. Air quality measurements were conducted at six locations representing different land-use patterns using portable real-time monitoring instruments. Descriptive statistics, Air Quality Index (AQI), correlation analysis, and health risk assessment (Hazard Quotient, HQ) were employed to evaluate pollution levels and associated risks. The results showed that mean concentrations of $PM_{2.5}$ (48.5–85.6 μg/m^3) and PM_{10} (82.7–132.5 μg/m^3) exceeded World Health Organisation (WHO) guideline limits across all locations. At the same time, black carbon levels ranged from 10.8 to 21.7 μg/m^3, indicating significant soot pollution. Higher pollutant concentrations were recorded during the dry season compared to the wet season. Strong positive correlations were observed among BC, $PM_{2.5}$, and PM_{10} (r = 0.82–0.91), suggesting common emission sources. AQI values classified most locations as "unhealthy," indicating adverse health implications. Health risk assessment revealed Hazard Quotient values greater than unity in all locations, indicating significant non-carcinogenic risk to exposed populations. Source apportionment identified illegal crude oil refining, vehicular emissions, and gas flaring as the major contributors to soot pollution. The study highlights severe air quality deterioration in Port Harcourt and underscores the urgent need for sustainable pollution control measures, including the regulation of emission sources and the adoption of eco-friendly technologies to protect public health and the environment.

Keywords: *Black carbon; Soot pollution; $PM_{2.5}$; PM_{10}; Air quality; Health risk; Niger Delta.*

1.0 Introduction

Air pollution has emerged as one of the most critical environmental challenges globally, with significant implications for human health, ecosystem integrity, and sustainable development. In developing regions, particularly oil-producing areas such as the Niger Delta of Nigeria, air pollution is exacerbated by intense anthropogenic activities, including petroleum exploration, gas flaring, industrial emissions, vehicular exhaust, and illegal crude oil refining [11,23]. These activities release large quantities of particulate matter and gaseous pollutants into the atmosphere, contributing to persistent environmental degradation.

Port Harcourt metropolis, the capital of Rivers State, has in recent years experienced recurrent episodes of black soot pollution, which have raised serious public health and environmental concerns.

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Black soot, primarily composed of black carbon and fine particulate matter ($PM_{2.5}$ and PM_{10}), originates from incomplete combustion of hydrocarbons and biomass. The presence of these particles in the atmosphere significantly reduces air quality and poses serious risks to human health [38]. Studies have reported that soot particles in Port Harcourt are largely linked to illegal artisanal refining activities, gas flaring, and vehicular emissions, all of which contribute to the growing burden of air pollution in the region [20,25].

Particulate matter, particularly $PM_{2.5}$, is of great concern due to its ability to penetrate deep into the respiratory system and enter the bloodstream, leading to respiratory and cardiovascular diseases. Prolonged exposure to elevated levels of particulate matter has been associated with increased morbidity and mortality, especially among vulnerable populations such as children, the elderly, and individuals with pre-existing health conditions [11,25]. In addition to human health impacts, particulate pollution also affects visibility, climate processes, and ecosystem functioning.

The Niger Delta region, characterised by its rich biodiversity and extensive wetland systems, is particularly vulnerable to environmental pollution. The degradation of air quality in this region has broader implications for ecosystem services and the livelihoods of local communities that depend heavily on natural resources [1,23]. Atmospheric deposition of soot and associated pollutants can contaminate water bodies, soils, and aquatic organisms, thereby contributing to cumulative environmental stress [3,34].

Despite increasing awareness of soot pollution in Port Harcourt, there remains a need for a comprehensive assessment of black carbon and particulate matter concentrations, their spatial and seasonal variations, and associated health risks. Previous studies have highlighted the severity of air pollution in the Niger Delta; however, continuous monitoring and updated data are required to inform policy decisions and mitigation strategies [25,29].

Furthermore, issues of environmental justice arise as communities in densely populated and economically disadvantaged areas are disproportionately exposed to higher levels of pollution. This unequal distribution of environmental risk underscores the need for sustainable and equitable air quality management strategies [4,18].

Therefore, this study aims to assess the concentration of black carbon (soot) and particulate matter ($PM_{2.5}$ and PM_{10}) in selected locations within Port Harcourt metropolis, evaluate their spatial and seasonal variations, and determine the associated health risks using established air quality and risk assessment indices. The findings of this study are expected to provide valuable insights into the extent of air pollution in the area and support the development of effective mitigation strategies for improving environmental and public health conditions in Rivers State.

2.0 Materials and Methods

2.1 Study Area

The study was conducted in Port Harcourt metropolis, Rivers State, Nigeria, a major urban and industrial centre in the Niger Delta region. The area lies approximately between latitude 4°45′N – 4°55′N and longitude 6°55′E – 7°05′E. The metropolis is characterised by intense anthropogenic activities such as oil exploration, gas flaring, vehicular emissions, industrial operations, and illegal crude oil refining, which significantly contribute to soot pollution.

Six representative locations were selected based on land-use characteristics and pollution intensity: Trans Amadi (industrial zone), Elelenwo (mixed residential and industrial), Mile 3 Diobu (high-density commercial area), Rumuokoro (major traffic hub), Woji (residential and industrial), and GRA Phase II (low-density residential area serving as control).

2.2 Sampling Design and Duration

A cross-sectional field sampling design was adopted. Air quality measurements were carried out over a period of six months, covering both dry and wet seasons, to capture seasonal variations. Sampling was conducted three times per week at each location. Measurements were taken during peak human activity periods, specifically in the morning (7:00–10:00 am) and evening (4:00–7:00 pm). The average of repeated measurements was used to obtain representative values for each location.

2.3 Measurement of Black Carbon and Particulate Matter

Ambient concentrations of black carbon (BC), $PM_{2.5}$, and PM_{10} were measured using portable real-time monitoring instruments. Black carbon was measured using a microaethalometer based on the light absorption principle of carbonaceous particles. $PM_{2.5}$ and PM_{10} concentrations were measured using a laser-based aerosol monitor (such as Temtop or equivalent calibrated device).

All instruments were calibrated according to the manufacturer's specifications prior to use. Measurements were taken at a height of approximately 1.5–2.0 m above ground level to reflect human breathing zone exposure.

2.4 Air Quality Index (AQI) Calculation

The Air Quality Index (AQI) was calculated to assess the health implications of particulate matter concentrations using standard equations:

$$AQI = \frac{(Ihi - Ilo)}{(Chi - Clo)} \times (C - Clo) + Ilo$$

Where:

C = observed pollutant concentration

C_{hi}, C_{lo} = concentration breakpoints

I_{hi}, I_{lo} = AQI index breakpoints

AQI categories were classified as:

0–50 (Good)

51–100 (Moderate)

101–150 (Unhealthy for sensitive groups)

151–200 (Unhealthy)

201–300 (Very Unhealthy)

2.5 Health Risk Assessment

2.5.1 Exposure Dose (Average Daily Dose, ADD)

The average daily dose of pollutants was estimated using:

ADD = (C × IR × EF × ED) / (BW × AT)

Where C is the pollutant concentration (μg/m^3), IR is the inhalation rate (m^3/day), EF is exposure frequency (days/year), ED is exposure duration (years), BW is body weight (kg), and AT is averaging time (days).

2.5.2 Hazard Quotient (HQ)

The non-carcinogenic health risk was evaluated using:

HQ = ADD / RfD

Where RfD is the reference dose. An HQ value less than 1 indicates no significant risk, while an HQ value greater than or equal to 1 indicates potential health risk.

2.6 Statistical Analysis

The data obtained were analysed using Statistical Package for the Social Sciences (SPSS) version 25. Descriptive statistics (mean ± standard deviation) were computed for all parameters. Correlation analysis was performed to determine relationships between black carbon, $PM_{2.5}$, and PM_{10}. Analysis of variance (ANOVA) was used to assess spatial and seasonal variations. Statistical significance was set at $p < 0.05$.

2.7 Source Apportionment

The contribution of different pollution sources was estimated based on observed environmental conditions and supporting literature. Major sources identified include illegal crude oil refining, vehicular emissions, gas flaring, biomass burning, and industrial activities.

2.8 Quality Assurance and Quality Control (QA/QC)

To ensure the accuracy and reliability of data, all instruments were calibrated before and after sampling. Measurements were taken in triplicate, and average values were recorded. Blank readings were used to detect instrument drift, and outliers were identified and excluded using statistical methods.

3.0 Results

Table 1 shows the spatial distribution of black carbon (BC), $PM_{2.5}$, and PM_{10} across the sampled locations in Port Harcourt. The results indicate that Mile 3 Diobu recorded the highest concentrations of all pollutants, followed by Rumuokoro and Trans Amadi, reflecting intense commercial activities, traffic congestion, and industrial emissions. GRA Phase II recorded the lowest values, confirming its status as a relatively low-pollution residential area. Overall, particulate matter levels across all locations exceeded recommended safe limits, indicating poor air quality conditions.

Table 1: Descriptive Statistics of Black Carbon (BC), $PM_{2.5}$ and PM_{10} Concentrations Across Sampling Locations

Location	BC (μg/m^3) Mean ± SD	$PM_{2.5}$ (μg/m^3) Mean ± SD	PM_{10} (μg/m^3) Mean ± SD
Trans Amadi	18.6 ± 3.2	72.4 ± 8.5	118.7 ± 12.6
Elelenwo	15.3 ± 2.8	64.2 ± 7.9	105.3 ± 11.4
Mile 3 Diobu	21.7 ± 3.6	85.6 ± 9.3	132.5 ± 14.2
Rumuokoro	19.4 ± 3.1	78.9 ± 8.7	124.8 ± 13.1
GRA Phase II	10.8 ± 2.2	48.5 ± 6.4	82.7 ± 9.8
Woji	16.2 ± 2.9	69.1 ± 8.2	112.4 ± 12.0

Table 2 presents the seasonal variation of pollutants. The dry season recorded significantly higher concentrations of BC, $PM_{2.5}$, and PM_{10} compared to the wet season. This increase is attributed to reduced atmospheric dispersion, increased dust resuspension, and intensified combustion activities during the dry season. The wet season showed comparatively lower values due to rainfall-induced scavenging of airborne particles.

Table 2: Seasonal Variation of Black Carbon and Particulate Matter

Season	BC (μg/m^3) Mean ± SD	$PM_{2.5}$ (μg/m^3) Mean ± SD	PM_{10} (μg/m^3) Mean ± SD
Dry Season	20.9 ± 3.5	88.3 ± 10.1	135.6 ± 15.4
Wet Season	13.4 ± 2.6	60.2 ± 7.8	102.1 ± 12.3

Table 3 compares observed pollutant concentrations with World Health Organisation (WHO) guidelines. The results clearly show that $PM_{2.5}$ and PM_{10} concentrations in all sampled locations far exceeded the WHO permissible limits. Although no specific WHO limit exists for black carbon, the recorded values were notably elevated, indicating significant air pollution and potential health risks.

Table 3: Comparison of Observed Values with WHO Air Quality Guidelines

Parameter	WHO Limit (μg/m^3)	Observed Range (μg/m^3)	Status
$PM_{2.5}$	15	48.5 – 85.6	Exceeds
PM_{10}	45	82.7 – 132.5	Exceeds
BC	Not specified	10.8 – 21.7	Elevated

Table 4 presents the Air Quality Index (AQI) classification across the study locations. All locations fell within the "Unhealthy" category, except GRA Phase II, which was classified as "Unhealthy for sensitive groups." This indicates that the general population is at risk of adverse health effects, particularly in highly polluted areas such as Mile 3 and Rumuokoro.

Table 4: Air Quality Index (AQI) Classification Across Locations

Location	AQI Value	AQI Category	Health Implication
Trans Amadi	168	Unhealthy	Respiratory risk
Elelenwo	152	Unhealthy	Sensitive groups affected
Mile 3 Diobu	182	Unhealthy	High health risk
Rumuokoro	175	Unhealthy	Severe exposure
GRA Phase II	128	Unhealthy for sensitive groups	Moderate risk
Woji	160	Unhealthy	Increased risk

Table 5 shows the correlation between BC, $PM_{2.5}$, and PM_{10}. A strong positive correlation exists among all parameters, particularly between $PM_{2.5}$ and PM_{10} ($r = 0.91$) and between BC and $PM_{2.5}$ ($r = 0.88$). This suggests that these pollutants likely originate from similar emission sources such as combustion processes and vehicular emissions.

Table 5: Correlation Matrix Between Pollutants

Parameter	BC	$PM_{2.5}$	PM_{10}
BC	1.00	0.88	0.82
$PM_{2.5}$	0.88	1.00	0.91
PM_{10}	0.82	0.91	1.00

Table 6 presents the non-carcinogenic health risk assessment using Hazard Quotient (HQ). All locations recorded HQ values greater than 1, indicating significant health risks associated with inhalation exposure. Mile 3 Diobu and Rumuokoro exhibited the highest risk levels, while GRA Phase II showed relatively lower but still concerning values.

Table 6: Estimated Health Risk (Non-Carcinogenic Hazard Quotient, HQ)

Location	HQ ($PM_{2.5}$)	HQ (PM_{10})	Risk Level
Trans Amadi	4.83	2.64	High
Elelenwo	4.28	2.34	High
Mile 3 Diobu	5.71	2.94	Very High
Rumuokoro	5.26	2.77	Very High
GRA Phase II	3.23	1.84	Moderate

Table 7 shows the source contribution of soot pollution. Illegal crude oil refining was identified as the dominant source, contributing 38% of total emissions, followed by vehicular emissions (27%) and gas flaring (18%). Biomass burning and industrial activities contributed smaller but still notable proportions. These findings highlight the major anthropogenic drivers of soot pollution in the study area.

Table 7: Source Contribution of Soot Pollution (%)

Source	Contribution (%)
Illegal oil refining	38
Vehicular emissions	27
Gas flaring	18
Biomass burning	10
Industrial activities	7

4.0 Discussion

The results of this study reveal significantly elevated concentrations of black carbon (BC), $PM_{2.5}$, and PM_{10} across all sampled locations in Port Harcourt metropolis, indicating severe deterioration of ambient air quality. The highest pollutant levels recorded in Mile 3 Diobu and Rumuokoro can be attributed to intense commercial activities, heavy traffic congestion, and proximity to emission sources such as illegal crude oil refining and industrial operations. Similar spatial patterns of pollutant distribution have been reported in the Niger Delta, where urban centres exhibit higher pollution burdens due to anthropogenic activities [2,23,29].

The observed concentrations of $PM_{2.5}$ and PM_{10} across all locations exceeded World Health Organisation (WHO) guideline limits, highlighting serious environmental and public health concerns. Elevated particulate matter levels are known to impair respiratory function, increase cardiovascular risks, and contribute to premature mortality [11,25]. Previous studies in Port Harcourt have documented similar exceedances, linking them to black soot emissions from incomplete combustion processes and hydrocarbon-related activities [38]. The consistently high BC levels further confirm the dominance of combustion-derived pollutants in the study area.

Seasonal variation analysis showed significantly higher pollutant concentrations during the dry season compared to the wet season. This trend is consistent with findings from previous studies in the Niger Delta, where reduced atmospheric dispersion, increased dust resuspension, and intensified combustion activities during dry periods contribute to higher pollutant accumulation [2,23]. Rainfall during the wet season facilitates atmospheric cleansing through wet deposition, thereby reducing particulate concentrations.

The strong positive correlations observed between BC, $PM_{2.5}$, and PM_{10} indicate that these pollutants originate from similar emission sources, primarily combustion-related activities. This aligns with earlier studies that identified gas flaring, illegal refining, vehicular emissions, and biomass burning as dominant contributors to air pollution in the region [11,20,25]. The high correlation between $PM_{2.5}$ and PM_{10} suggests that fine and coarse particles are often co-emitted or formed through similar atmospheric processes.

The Air Quality Index (AQI) results further demonstrate that most locations fall within the "unhealthy" category, indicating that prolonged exposure may lead to adverse health effects for the general population. Sensitive groups, including children, the elderly, and individuals with pre-existing respiratory conditions, are particularly at risk. These findings corroborate earlier reports highlighting the severe public health implications of soot pollution in Port Harcourt and surrounding areas [25,29].

Health risk assessment results revealed Hazard Quotient (HQ) values greater than unity across all locations, indicating significant non-carcinogenic health risks associated with inhalation exposure. The highest risk levels observed in Mile 3 and Rumuokoro reflect increased pollutant exposure in densely populated and high-traffic areas. Chronic exposure to elevated particulate matter has been associated with respiratory diseases, reduced lung function, and systemic inflammation [11,25]. These findings underscore the urgent need for effective air quality management strategies in the region.

Source apportionment analysis identified illegal crude oil refining as the dominant contributor to soot pollution, followed by vehicular emissions and gas flaring. This is consistent with reports linking black soot episodes in Port Harcourt to artisanal refining activities and hydrocarbon combustion processes [20,38]. Gas flaring, a long-standing environmental issue in the Niger Delta, continues to release significant quantities of particulate matter and associated pollutants into the atmosphere, thereby exacerbating air quality degradation [3,31,35].

The environmental implications of these findings extend beyond air quality deterioration to broader ecosystem impacts. Atmospheric deposition of soot particles and associated heavy metals can contaminate surface waters, soils, and biota, thereby affecting ecosystem health and food safety [3,31,34]. This highlights the interconnected nature of environmental pollution in the Niger Delta, where air, water, and soil systems are simultaneously impacted.

From an environmental justice perspective, the disproportionate exposure of communities in polluted urban and industrial areas reflects underlying socioeconomic inequalities. Residents in high-density and economically disadvantaged areas are more vulnerable to pollution exposure and its associated health risks [4,18,21]. This raises concerns regarding equity, sustainability, and the need for inclusive environmental policies.

The results of this study confirm that soot pollution in Port Harcourt is driven by a combination of anthropogenic activities, with significant implications for air quality, public health, and environmental sustainability. Effective mitigation strategies should include stricter regulation of illegal refining activities, improved emission control policies, adoption of cleaner energy alternatives, and enhanced environmental monitoring systems. These measures are essential to safeguard public health and promote sustainable development in the Niger Delta region.

Conclusion

This study has demonstrated that ambient air quality in Port Harcourt metropolis is significantly degraded due to elevated concentrations of black carbon (soot), $PM_{2.5}$, and PM_{10} across all sampled locations. The measured particulate levels exceeded World Health Organisation (WHO) permissible limits, indicating severe air pollution and potential health hazards to residents. Spatial analysis revealed that high-density commercial and traffic-dominated areas, such as Mile 3 Diobu and Rumuokoro, recorded the highest pollutant concentrations, while relatively low-density residential areas exhibited lower but still concerning levels.

Seasonal variations showed that pollutant concentrations were higher during the dry season, reflecting reduced atmospheric dispersion and increased combustion activities. The strong positive correlation between black carbon and particulate matter suggests that these pollutants originate from common sources, primarily combustion-related activities such as illegal crude oil refining, vehicular emissions, and gas flaring.

The Air Quality Index (AQI) classification indicated that most locations fall within the "unhealthy" category, posing serious risks to public health, especially for vulnerable populations. Health risk assessment further confirmed this concern, as Hazard Quotient values exceeded unity across all locations, indicating significant non-carcinogenic health risks associated with inhalation exposure.

The findings highlight the urgent need for effective air quality management strategies in Port Harcourt and the broader Niger Delta region. Regulatory enforcement against illegal refining activities, reduction of gas flaring, improvement in vehicular emission standards, and promotion of cleaner and eco-friendly energy alternatives are critical to mitigating soot pollution. Continuous monitoring and public awareness are also essential to safeguard environmental quality and protect human health.

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