Health Risk Implications of $PM_{2.5}$, PM_{10}, Vocs, and Formaldehyde at Waterfront Residential Buildings of Port Harcourt Metropolis Rivers State

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Abstract
Indoor air pollution in waterfront communities of Port Harcourt poses significant public health concerns due to poor housing conditions, marine activities and inadequate ventilation. This study assessed the indoor air concentrations of $PM_{2.5}$, PM_{10}, VOCs, and formaldehyde (HCHO) in ten waterfronts communities namely Rex Lawson Waterfront, Eagle Island Waterfront, Bundu Ama Waterfront Elechi Beach Waterfront, Enugu Waterfront, Ibadan Waterfront, Marine Base Waterfront, Okirika Waterfront, Slaughter Waterfront and Woji Waterfront and ten residential building in each of the communities. Associated health risks were also evaluated using Hazard Quotient (HQ), Hazard Index (HI), and Cancer Risk (CR) models. Statistical analysis (mean, standard deviation, and coefficient of variation) was performed to evaluate spatial variability. Results showed that the mean concentration for each parameter showed that, $PM_{2.5}$ ranged from (8.5–16.65 µg/m³ with a mean of 12.20 ± 2.55) and PM_{10} ranged from (23.95–35.7 µg/m³, with a mean of 28.85 ± 3.36). $PM_{2.5}$ in all locations was within the WHO 24-hour guideline (15 µg/m³) except in Woji where it exceeded permissible limit. PM_{10} in all location was within the WHO 24-hour guideline (45 µg/m³) but exceeded the WHO annual guideline (15 µg/m³) across all locations. VOCs (0.030–0.053 mg/m³) and HCHO (0.020–0.045 mg/m³) remained below WHO-referenced indoor air thresholds. Hazard Index values (3.95–5.89) exceeded unity in all sites, indicating significant non-carcinogenic risk. Cancer risk from HCHO (2.6×10^{-7} – 5.85×10^{-7}) remained within USEPA acceptable limits but indicates chronic exposure concern.

Keywords: *Indoor air pollution, Waterfront, $PM_{2.5}$, PM_{10}, VOCs, formaldehyde, WHO guidelines, USEPA, health risk assessment*

Introduction
Air pollution is the leading environmental health risk, with 92% of the global population exposed to substandard air quality, living in areas where the concentration of air pollutants exceeds safe levels (WHO, 2008). Air quality, both indoor and outdoor, has a profound effect on human health and general well-being. It is estimated that approximately 6.5 million deaths occur globally each year due to air pollution, making it the fourth leading health threat worldwide following high blood pressure, dietary risks and smoking (WHO, 2008). Compare to outdoor pollution, indoor air pollution is of greater concern in countries worldwide, affecting both developing and developed nations. Since people spend most of their time

indoor, exposure to indoor air pollutants greatly affects both their health and productivity in the workplace (Meciarova et al., 2017). However, research on air quality has mostly focused on the outdoors, whereas indoor air quality (IAQ) and its impacts have received considerably less attention until the last decade (Sundell, 2004). Due to continuous changes in living style and the materials used in indoor environments, there have been significant changes in terms of the nature and complex compositions of indoor air pollutants, which open up avenues that need to be investigated in detail. Air pollutant with smaller particulate size poses more danger as they are able to infiltrate lungs and cause severe health effects such as asthma, chronic obstructive pulmonary disease or increased cardiovascular risks (Gauderman et al., 2007; WHO, 2006). Indoor air quality refers to the condition within and around buildings and structures, particularly as it relates to health and comfort of occupants. According to Sani et al. (2023), most people spend an average of 80 to 90% of their time indoors both in developed and developing countries, most of which is at home. This built environment has a tremendous impact on health, wellbeing and general quality of life (Sani et al., 2023). These impacts are enunciated in their originating source, dispersion, travel time, travel distance, particle size, modifications, metamorphoses, consequences and repercussions. Poor indoor air quality has been linked to variety of health issues, from short-term effects such as irritation eyes, nose and throat to long term effects including respiratory diseases such as sinusitis, mild otitis, olfactory impairment, rhinitis and Sino nasal cancer (Shusterman, 2011). In densely populated urban areas such as Port Harcourt Metropolis, environmental challenges due to rapid urbanization, industrial activities, and socio-economic disparities contribute to diverse living conditions, which greatly affect air quality.

Port Harcourt Metropolis, the capital city of Rivers State, Nigeria, serves as an economic and industrial hub within the Niger Delta region. It is primarily made up of two main Local Government Area (LGAs). The Port Harcourt City LGA and The Obio/Akpor Local Government Area. Port Harcourt Metropolis has experienced rapid population growth due to its status as a center for economic opportunities, primarily driven by the oil and gas industry. It combines residential, commercial, and industrial zones, leading to a complex urban layout. The population is diverse, comprising various ethnic groups, with the Ijaw, Ikwerre, Okrikas and Ogoni people being prominent. The urbanization rate has led to significant migration from rural areas and other states, contributing to a densely populated city. This growth rate is the leading cause of people migrating and forming various settlements along the waterfront. The waterfront themselves are becoming overcrowded, leading to the characterization of the city by its division into Waterfront and Inland areas in this research.

As of the 2006 population census, Port Harcourt Metropolis recorded a population of 1,005,904. Recent population estimates, according to the National Population Commission of Nigeria and United Nations data, puts the population of Port Harcourt Metropolis to be between 1.8 to 2.1 million people, with projections indicating continued growth due to urban migration and natural population increase. This rapid population growth has led to challenges such as traffic congestion, housing deficits leading to more sprawling settlements and environmental degradation, which adversely impact more on air quality, especially waterfront areas, which experience intensified exposure to indoor air pollution due to poor housing characterization, ventilation, misused of chemicals (insecticides, rodenticides), combustion activities commonly called “kpo fire”, and proximity to marine- industrial emissions. According to the World Health Organization (WHO, 2021), particulate matter is among the most harmful pollutants globally, while the United States Environmental Protection Agency (USEPA, 2023) classifies $PM_{2.5}$ and formaldehyde as critical health risk agents.

Study Area

Description of the Study Area

The study area Port Harcourt Metropolis is in Rivers State; and is located in the Niger Delta region of Nigeria. The Niger Delta is located on the West African continental margin where the east trending Equatorial coast turns south towards the Equator (Chiadikobi et al., 2011). The state is bounded by the Atlantic Ocean to the south, Akwa-Ibom State to the west, Bayelsa and Delta States to the east and Anambra, Abia and Imo States to the north. The city of Port Harcourt is situated between latitudes $4^{0}45'$N and $4^{0}55'$N and longitudes 6°55'E and $7^{0}05'$E. It is roughly 66 kilometers away from the Atlantic Ocean. Eludoyin et al. (2011), reported that Obio/Akpor LGA is located between latitudes 4º 45'N and 4º60'N and longitudes 6º 50'E and 8º00'E. Physically, Port Harcourt metropolis spread has happened in both a south – easterly and a northerly heading course (Ameme et al., 2022), giving rise to several Waterfront settlements within Port Harcourt metropolis, Niger Delta, Nigeria.

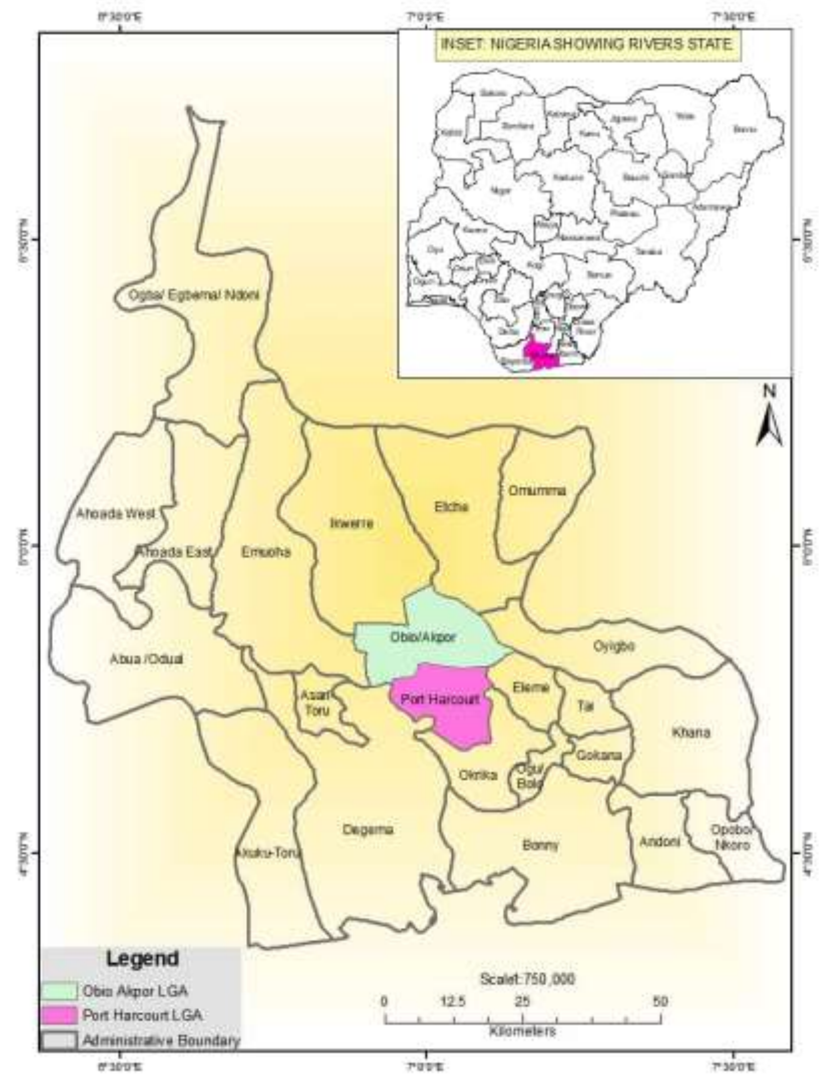

Figure1: Map of Rivers State in Nigeria Showing Study Areas

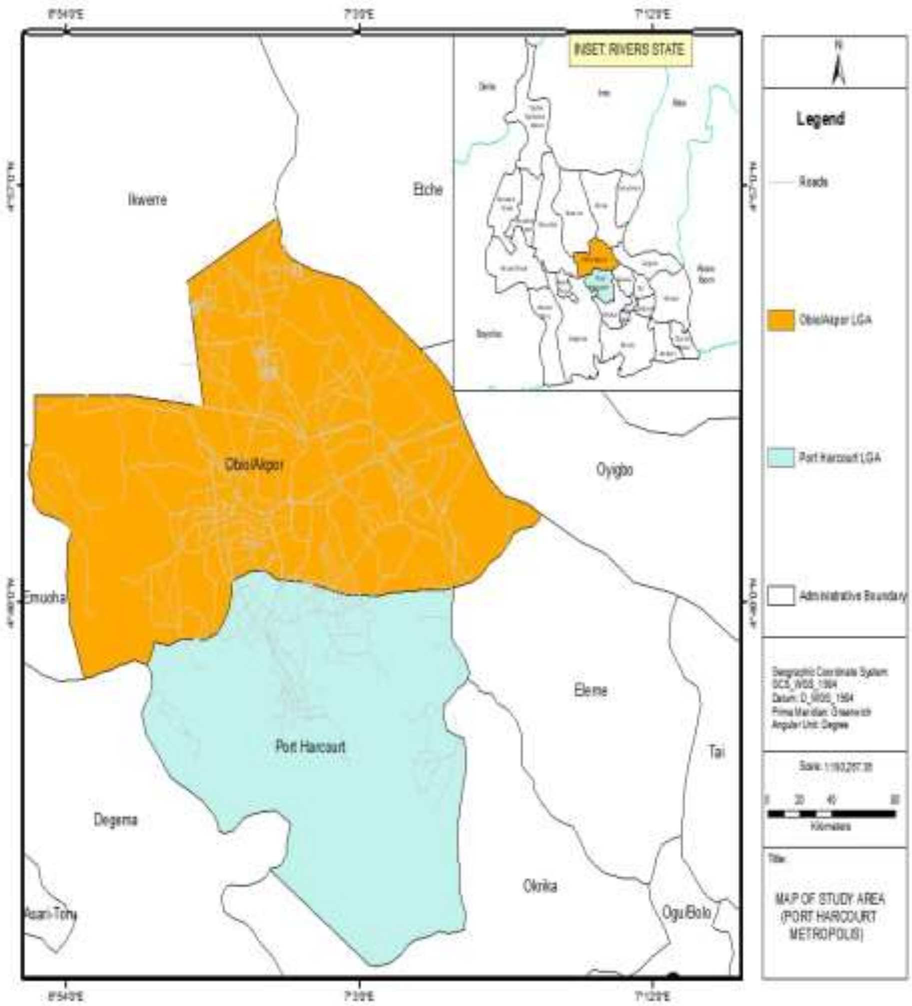

Figure 2: Map of Port Harcourt City and Obio/Akpor Local Government Areas in Rivers State

Materials and Methods

Sampling Equipment

The materials employed in this study were portable hand-held equipment Bosean Gas Detector; Model:BH-4S Multi Gas Detector and Blatn BR Smart Portable Air Quality monitor. The concentration levels of PM2.5, PM10, VOCs, HCHO were determined using Bosean Gas Detector; Model:BH-4S Multi Gas Detector, which has been calibrated. This Bosean gas detector often support multiple parameters, hence the parameters to be detected were chosen using specific buttons and settings provided. The detector was allowed some time to sense and measure parameters concentration. The digital display was monitored and real-time concentration levels recorded. Measurement was carried out three times for each parameter and the average calculated.

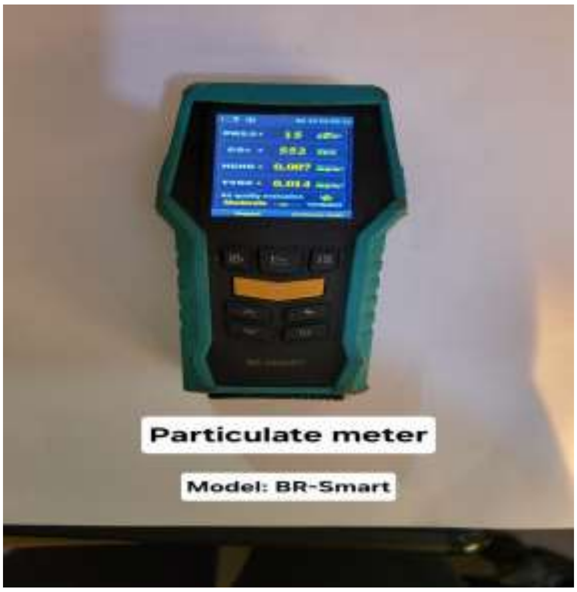

Plate 1: Portable Hand-Held Air Quality **Measurement Device**

Plate 2: Portable Hand-Held Multi-Gas Detector

Methodology

Pollutants Measured were $PM_{2.5}$ (µg/m³), PM_{10} (µg/m³), VOCs (mg/m³) and HCHO (mg/m³). The Health Risk Assessment was measured using USEPA/WHO based risk models.

Hazard Quotient (HQ):

$$HQ = \text{Concentration}/RFC$$

Where C is the measured concentration, RFC is the reference guideline value.

Hazard Index (HI): The summation of all pollutant per location, $HI=\sum HQ$. If $HQ>1$, this indicate potential non carcinogenic risk and if $HI>1$, then combined risk

Cancer Risk (CR):

$$CR = \text{Concentration} \times IUR$$

Where IUR (Inhalable Unit Risk) $=1.3 \times 10^{-5}$

The WHO and USEPA Standards used for assessment is given as below:

Table 1: WHO (2021) and USEPA (2023) Standards

Pollutant	WHO Limit	USEPA Reference
$PM_{2.5}$	5 µg/m³ (annual), 15 µg/m³ (24-hr)	12 µg/m³ annual
PM_{10}	15 µg/m³ (annual), 45 µg/m³ (24-hr)	150 µg/m³ (24-hr)
HCHO	0.1 mg/m³ (short-term guideline)	Classified carcinogen
VOCs	~0.3 mg/m³ (indoor guideline)	Variable compounds

Statistical Analysis analysis such as the Mean ($\bar{x}$), Standard Deviation (SD), Coefficient of Variation (CV%) and Range (Min–Max) was also used for assessment.

Results and Discussion

Table 2: Comparative Indoor Air Pollution Exposure and Health Risk Ranking Across Study Locations in Port Harcourt Waterfront Communities. ($PM_{2.5}$ (µg/m³) PM_{10} (µg/m³))

Rank	Location	$PM_{2.5}$	PM_{10}	WHO $PM_{2.5}$ Status	WHO PM_{10} Status	HI	CR(HCHO)	Risk Category
1	Woji	16.65	35.7	Exceeds 24-hr (15)	< 24-hr /> annual	5.89	3.9×10^{-7}	Very High
2	Okrika	13.73	34.3	Below 24-hr	< 24-hr / > annual	5.45	5.85×10^{-7}	Very High
3	Ibadan	14.3	30.0	Near limit	<24-hr / > annual	5.43	5.2×10^{-7}	Very High
4	Elechi Beach	13.6	30.0	Below 24-hr	< 24-hr / > annual	5.23	2.6×10^{-7}	Very High
5	Rex Lawson	12.8	29.1	Below 24-hr	<24-hr /> annual	5.05	2.73×10^{-7}	High
6	Slaughter	12.2	27.85	Below 24-hr	<24-hr /> annual	4.87	3.9×10^{-7}	High
7	Marine Base	10.1	25.8	Below limit	<24-hr /> annual	4.23	2.6×10^{-7}	Moderate–High
8	Eagle Island	10.2	26.5	Below limit	<24-hr /> annual	4.18	2.6×10^{-7}	Moderate–High
9	Enugu	9.9	25.3	Below limit	<24-hr />annual	4.04	2.6×10^{-7}	Moderate
10	Bundu	8.5	23.95	Lowest	Lowest	3.95	2.6×10^{-7}	Moderate

Table 3: Descriptive Statistics of Pollutants

Parameter	Mean ± SD	Range	CV (%)
$PM_{2.5}$	12.20 ± 2.55	8.5–16.65	20.9
PM_{10}	28.85 ± 3.36	23.95–35.7	11.6
VOC	0.048 ± 0.006	0.03–0.053	12.5
HCHO	0.026 ± 0.008	0.02–0.045	30.8

Highest variability observed in HCHO (CV = 30.8%), indicating uneven indoor chemical sources.

The results shows that $PM_{2.5}$ exceeded WHO 24-hr limit (15 µg/m³) in Woji. PM_{10} was below WHO 24-hr limit but exceeds annual guideline (15 µg/m³) in all sites. VOCs & HCHO were **b**elow WHO-referenced indoor limits

The Health Risk Assessment shows the health index in table 4

Table 4: Hazard Index (HI)

Location	HI
Woji	5.89
Ibadan	5.43
Enugu	4.04
Okrika	5.45
Elechi Beach	5.23
Rex Lawson	5.05
Slaughter	4.87
Marine Base	4.23
Eagle Island	4.18
Bundu	3.95

All HI > 1 → significant health risk

The results of the health index shows that all locations were more than one indicating a significant health risk

The Cancer Risk for (HCHO) Range ranged from 2.6×10^{-7} – 5.85×10^{-7} which shows that value is well below USEPA risk threshold (10^{-6} – 10^{-4}) indicating a low but persistent lifetime risk.

Discussion

The risk assessment presented in Table 2 provides a clear spatial characterization of indoor air pollution exposure and associated health risks across waterfront. The findings demonstrate marked variability in pollutant concentrations and health risk indices, with a consistent dominance of particulate matter ($PM_{2.5}$ and PM_{10}) as the primary driver of non-carcinogenic health risks. A distinct spatial gradient was observed, with Woji, Okrika, and Ibadan ranking as the highest-risk locations. These sites recorded the highest $PM_{2.5}$ concentrations (13.73–16.65 µg/m³) and Hazard Index (HI) values exceeding 5.4. This suggests intensified exposure likely associated with a combination of poor indoor ventilation, high occupancy density, and infiltration of outdoor emissions, including marine activities, industrial activities, and combustion sources typical of waterfront and peri-urban environments. Conversely, Bundu and Enugu exhibited relatively lower pollutant loads and hazard indices (HI ≈ 3.9–4.04), indicating comparatively reduced exposure intensity. However, even in these "lower-risk" locations, HI values remained significantly above unity, confirming that no studied environment is free from health risk implications. Particulate Matter is the dominance in Risk Contribution. Across all locations, $PM_{2.5}$ consistently emerged as the dominant contributor to the Hazard Index. This is consistent with established toxicological evidence that fine particulate matter penetrates deep into the alveolar region, inducing systemic inflammatory responses and increasing risks of cardiopulmonary morbidity and mortality (WHO, 2021).
Although PM_{10} concentrations were generally below the WHO 24-hour guideline (45 µg/m³), they exceeded the annual mean guideline (15 µg/m³) across all sites. This indicates a pattern of chronic exposure rather than acute episodic pollution, which is particularly relevant for long-term health outcomes. The Chemical Pollutants and Relative Risk Contribution shows that Volatile organic compounds (VOCs) and formaldehyde (HCHO) exhibited relatively low hazard quotients compared to particulate matter. However, their presence remains toxicologically relevant due to their cumulative and chronic exposure effects, particularly in poorly ventilated indoor environments. Formaldehyde concentrations were highest in Okrika (0.045 mg/m³) and Ibadan (0.040 mg/m³), resulting in slightly elevated cancer risk estimates (up to 5.85×10^{-7}). Although all values fall within the USEPA acceptable lifetime cancer risk range (10^{-6}–10^{-4}), the continuous exposure pattern suggests a potential long-term public health concern, especially for vulnerable groups such as children and the elderly.
The Integrated Health Risk Interpretation shows that Hazard Index values across all locations ranged from 3.95 to 5.89, far exceeding the threshold value of unity. This indicates that residents are simultaneously exposed to multiple pollutants at levels capable of producing combined non-carcinogenic health effects. The risk ranking highlights three priority zones: High-risk cluster: Woji, Okrika, Ibadan; Moderate–high risk cluster: Elechi Beach, Rex Lawson, Slaughter and Moderate risk cluster: Marine Base, Eagle Island, Enugu, Bundu
This classification reflects a clear exposure burden hierarchy, which is strongly driven by particulate matter concentrations rather than gaseous pollutants. The observed exposure levels have significant implications for respiratory and cardiovascular health. Continuous exposure to elevated $PM_{2.5}$ and PM_{10} is associated with increased risks of: Chronic obstructive pulmonary disease (COPD), Asthma exacerbation, Hypertension and ischemic heart disease and Systemic inflammation and reduced lung function. Given the cumulative HI values, the study suggests that residents are experiencing chronic multi-pollutant exposure stress, rather than isolated pollutant effects. The uniform annual exceedance of WHO guideline values for particulate matter across all locations indicates a systemic indoor air

quality problem rather than localized pollution events. Therefore, it is important to have improved housing ventilation systems, reduction in combustion-based indoor activities and environmental health surveillance in waterfront communities. The dominance of $PM_{2.5}$ and PM_{10} indicates strong influence of combustion sources and poor ventilation. According to **WHO (2021)**, no safe level of $PM_{2.5}$ exposure exists, reinforcing the observed health risk burden. Spatial variability (high CV in HCHO) suggests localized emission sources such as building materials and indoor fuel use. USEPA classifies $PM_{2.5}$ as a major contributor to premature mortality, supporting the high HI values observed.

Conclusion

Indoor air pollution in waterfront communities of Port Harcourt is characterized by elevated particulate matter and moderate chemical pollutant exposure. While VOCs and HCHO remain within guideline limits, particulate matter significantly exceeds WHO thresholds, resulting in high health risk indices. There is a urgent need to carry out more indoor air quality, especially for vulnerable population like children, people with health challenges related to respiration and the elderly, implement indoor air quality monitoring systems and enforce environmental health policies in waterfront settlements.

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