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Monitoring of Air Quality for Particulate Matter ($PM_{2.5}$, PM_{10}) and Heavy Metals Proximate to a Cement Factory in Ewekoro, Nigeria

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Abstract

A cement factory nearby communities raise pollution concerns. This study assessed air pollution levels for respirable particulate matter ($PM_{2.5}$ and PM_{10}) and heavy metals (lead, chromium, nickel, cadmium, zinc and copper) adjacent to a cement factory in Ewekoro and neighbouring communities (Papalantoro, Lapeleko and Itori) in Ogun State, Nigeria. Respirable particulate matter ($PM_{2.5}$ and PM_{10}) and heavy metals were measured using an ARA N-FRM cassette sampler. Each location sampled was monitored for eight continuous hours daily for 12 days. The $PM_{2.5}$, PM_{10} and heavy metals results were compared with different standards, including those of the World Health Organization (WHO), Nigeria's National Environmental Standard and Regulation Enforcement Agency (NESREA) and Canadian Ambient Air Quality Standards (CAAQS). The PM levels fell within 11 - 19 μg/m^3 of the air management level of CAAQS, which signifies continuous actions are needed to improve air quality in the areas monitored but below the NESREA standard. The mean Cd, Cr and Ni concentrations in the cement factory area and the impacted neighbourhoods are higher than the WHO/EU permissible limits, while Zn and Cu were below the WHO/EU permissible limit. A risk assessment hazard quotient (HQ) for Cr was above the WHO/EU safe level (=1) in adults and children through ingestion, inhalation and dermal contact at all the monitoring sites. The HQ for Ni and Cd was higher than the safe level in the cement factory area and Papalantoro, while Zn was at safe levels.

Keywords

Particulate Matter, Heavy Metals, Air Sampling, Cement Factory Pollution, Hazard Quotient, Cement, Industrial Pollution

1. Introduction

The cement industry is a major source of pollutants worldwide, producing negative health impacts, global warming and acid rain (Ige et al., 2021). The cement industry accounts for approximately one-quarter (25% - 27%) of global industrial emissions and 5% - 7% of carbon dioxide (CO_2) emissions (Etim et al., 2021). The cement industry is one of the biggest polluters of CO_2 emissions, particulate matter, and acid rain, and it is a major fossil fuel user. Cement production emits large amounts of particulate matter (PM), nitrogen dioxide (NO_2), carbon monoxide (CO), and sulfur dioxide (SO_2) (Oluseyi et al., 2011; Etim et al., 2021).

Cement industry emissions pollute the air, water and soil (Oluseyi et al., 2011). Particulate matter emissions from cement production come from different sources, including the kiln, power plants, packing sections, heavy vehicles and blasting areas. These sources cause a significant amount of particulate matter to be discharged into the atmosphere. For example, the cement industry in Russia releases about 27 million tonnes of particulate dust per year into the atmosphere (Strizhenok & Ivanov, 2017). The dispersion and migration of the particulate matter are associated with the prevailing wind speed and directions (George et al., 2008; Ibe et al., 2017; Jurado et al., 2021). Cement dust is deposited on the earth's surface throμgh dry deposition and, when precipitating, wet deposition, impacts human health.

Cement pollution in Nigeria is an environmental and health problem. Nigeria has the largest cement industry in West Africa, with adjacent communities to these industries facing serious environmental and health issues (Okoro et al., 2017; Etim et al., 2021). Air pollution from cement production has been linked to serious health risks and decreased the quality of life for workers and local people living nearby (Sooktawee et al., 2020; Etim et al., 2021).

Particulate matter contributes to cardiovascular and respiratory diseases (Rai, 2015). The most vulnerable groups are young children, older people with underlying respiratory conditions, workers and neighbouring communities (Etim et al., 2021). In 2017, 49,100 child/youth deaths in Nigeria were linked to atmospheric $PM_{2.5}$, with children under the age of five most vulnerable, accounting for over 60% of all $PM_{2.5}$-induced deaths (Oki et al., 2018). An extensive review of medical records and the health status of those living near cement industries in Nigeria revealed high illness and death rates from cement dust (Etim et al., 2021; Oki et al., 2018).

This paper focuses on the emissions from the Lafarge Ewekoro Cement Factory in Nigeria, considering the health impact of pollution in nearby communities. The factory has been a major source of environmental problems since opening in 1959 (Afolabi et al., 2012). This paper investigated and assessed the air pollution levels at this cement factory at Ewekoro and the neighbouring communities—Papalantoro, Lapeleko, and Itori—in southwestern Nigeria. Particulate matter and metal levels in the air were measured in these areas to ascertain the impact of cement production on nearby air quality. The methods involved monitoring the pollutant level at the cement industry and neighbouring communities. The pollution levels are compared to different standards, and a hazard quotient assessment is conducted to understand the health impacts of the Lafarge Ewekoro cement factory on the neighbouring communities. Human health risk exposure assessment of heavy metals for non-carcinogenic risk in the air is measured for each community.

2. Materials and Methods

2.1. Study Area

This study was conducted in Ewekoro and surrounding settlements nearby the Ewekoro Lafarge Cement Factory of Ogun State, Nigeria. The cement facility is situated along the Lagos-Abeokuta Express Road at latitudes 6˚54'N and 6˚55'N and longitudes of 3˚12'E and 3˚13'E (Figure 1). The town is largely rural and known for its rich natural resources. The town has a total land area of 594 km^2 and a population of 108,944 inhabitants.

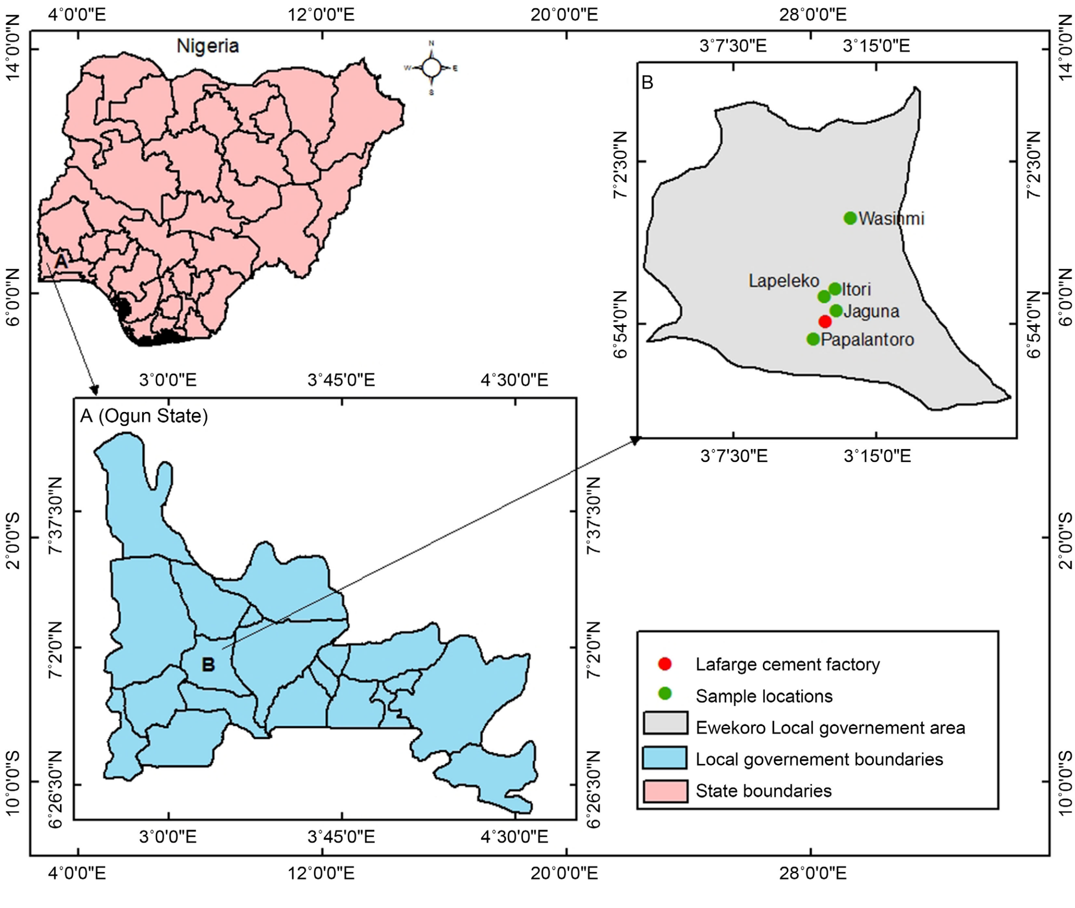


Figure 1. Map locating the Lafarge cement factory and nearby communities sampled.

The Ewekoro Lafarge Cement Factory is Nigeria's oldest cement factory. Since being established in 1959 in Ewekoro, the cement factory has contributed greatly to the state's economy. The limestone rock in this region provided the cement material (Agbede et al., 2022). About 1.8 million tonnes of cement are produced annually from the Lafarge Cement Factory. The production technology evolved from a semi-wet system in 1960 to a wet system in 1978 and a fully dry system in 2002. Each of these systems produced different levels of pollution (Agbede et al., 2022).

The Lafarge Cement Factory in Ewekoro has been a major source of environmental problems since its opening (Afolabi et al., 2012). Environmental pollution caused by the Lafarge Cement Factory is a major problem with serious health consequences for Ewekoro residents and nearby settlements. Cement production releases toxic emissions into the air, including dust particles, carbon dioxide, nitrogen oxide, suspended particulate matter, and heavy metals (Oluseyi et al., 2011). In addition, effluent discharge into the Akinbo River is also of major concern (Agbede et al., 2022).

2.2. Data Collection

2.2.1. Air Sampling Procedure

Air monitoring for $PM_{2.5}$ and PM_{10} was carried out in the study area eight hours daily for 12 days (96 hours). This sampling was done during the dry season for each sampling site. The neighbourhoods were inspected to choose appropriate sampling sites based on their proximity to the cement factory.

An ARA N-FRM air sampler, an alternative to the Federal US EPA Federal Reference Method (FRM) (also called near FRM, or n-FRM), was used to monitor the air quality for PM_{10} and $PM_{2.5}$ concentrations at locations near the cement factory. The ARA N-FRM air sampler is a battery-operated, portable air sampler fitted with a PEET anemometer. The sampler has a 47 mm filter cassette that traps air pollutants, which can be further analyzed in the laboratory (ARA Instruments, 2024).

The particulate sampler chosen is a new class of air sampler. Althoμgh not a certified US EPA Federal Reference Method (FRM), the particulate sampler is "near FRM" and can be validated (ARA Instruments, 2024). The ARA N-FRM sampler delivers FRM accuracy at a tiny fraction of the cost (ARA Instruments, 2024). The ARA N-FRM air sampler has an automated weather station device that measures the locations' wind direction, speed, and pressure. The ARA N-FRM (**Figure 2**) is an affordable, readily accessible particulate monitoring system that boosts air quality surveillance networks for spatial and local variations in PM concentrations (Solademi & Thompson, 2023).

The sampler was calibrated according to the instruction manual before each sampling event to reduce the sampling error. The sampler was set at nose height, 5.5 feet above the ground. **Table 1** lists the sampling locations near the Ewekoro Lafarge Cement factory with their geographical coordinates and characteristics.

The air was monitored for eight continuous hours daily, from approximately 10:00 am to 6:00 pm. The air sampler logs the $PM_{2.5}$ and PM_{10} μg/m^3 values every 15-minute interval for eight hours. Air quality at the cement factory area was monitored for four days (32 hours), i.e. eight continuous hours daily. The blasting/production area (BPA) was monitored for (16 hours) and the Packaging area (PA) (16 hours) in the cement factory area, respectively, totaling 32 hours of monitoring in the cement factory area. Air quality at Papalantoro was monitored for three days (24 hours), Lapeleko for three days (24 hours) and Itori for two days (16 hours).

Figure 2. Air monitoring at the impacted neighbourhood Lapeleko on the 26th of March 2024 with ARA N-FRM.

Table 1. Air sampling locations proximate to Ewekoro's Lafarge Cement factory and distance from the factory.

Sampling Location	Coordinates		Designation for distance from the factory NOTE: prevailing northwest winds are variable
	Latitude	**Longitude**	
Blasting area (BPA1)	6.9078951	3.1812388	1 km west of the factory but south of blasting area
Blasting area (BPA2)	6.9070739	3.1877185	2 km west of the factory but south of the blasting area
Packaging area (PA1)	6.9028311	3.2090876	500 m east of the factory
Packaging area (PA2)	6.8989988	3.2093633	600 m east of the factory
Papalantoro 1	6.8864069	3.1962661	1 km south of the factory/Impacted neighbourhoods
Papalantoro 2	6.8877756	3.1975069	1.5 km south of the factory/Impacted neighbourhoods
Papalantoro 3	6.8891443	3.2002642	1.2 km south of factory/Impacted neighbourhoods
Lapeleko 1	6.9234974	3.2048137	2 km north of the factory/Impacted neighbourhoods
Lapeleko 2	6.9240448	3.2060545	2.2 km north of the factory/Impacted neighbourhoods
Lapeleko 3	6.9252766	3.2064681	3 km north of the factory/Impacted neighbourhoods
Itori 1	6.9408783	3.2188760	4 km north of the factory/Impacted neighbourhoods
Itori 2	6.9373200	3.2219090	4.3 km north of the factory/Impacted neighbourhoods

Figure 3 shows the map sampling points near the cement factory (the blasting/production area and the packaging area) and the impacted neighbourhoods, Papalantoro, Lapeleko, and Itori. The cement factory is very close to residential settlements and communities, and its activities harm neighbouring communities.

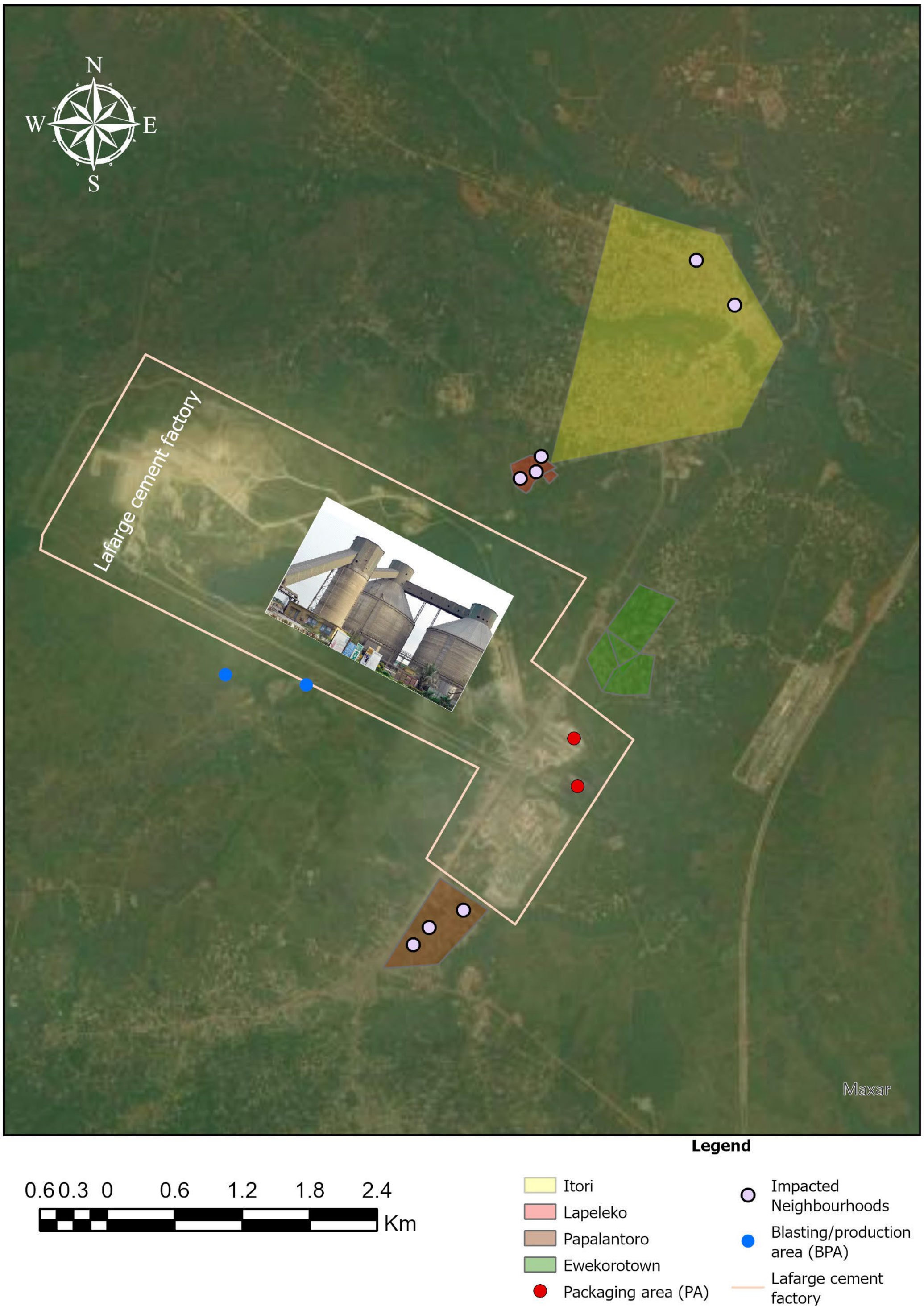


Figure 3. Sampling points at the Lafarge Ewekoro Cement Factory pollution in Nigeria and adjacent neighbourhoods.

2.2.2. Validation and Reference to a Standard of ARA N-FRM Air Sampler

Krμg et al. (2021) validated the data recorded by the ARA N-FRM sampler through collocation with designated EPA $PM_{2.5}$ FRM and Tisch Environmental (Cleves, OH) Model TE-WILBUR filter-based FRM samplers. The ARA N-FRM was the only small filter-based sampler to meet accuracy standards for EPA $PM_{2.5}$ FRM mass measurement performance criteria. The ARA Instruments model N-FRM sampler satisfies the performance specifications of the FRM standards and guidelines for $PM_{2.5}$ mass measurement accuracy in both simulated wild fire circumstances (98.2% ± 1.4%) and average ambient conditions (97.3% ± 1.9%). According to Krμg et al. (2021), the validity of ARA N-FRM with Tish FRM PM2.5 air monitoring showed $r^2 = 0.99$ and $r^2 = 0.99$ for ambient and chamber testing.

2.2.3. Analysis of Heavy Metals Concentrations in Particulate Matters

The 47 mm filter cassette in the ARA N-FRM tapped air pollutants Which were then analyzed in the laboratory. The exposed filter paper sample was cut into pieces and then digested. The cut filter was transferred into a glass tube, with 5 ml of mixed acid extractant, 65 ml concentrated (conc.) nitric acid and 185 ml conc. hydrochloric acid dissolved in 1L of deionized distilled water. The acid sample was heated at 1000 C for 30 minutes in a water bath and 500 degrees C for 30 minutes in an ultrasonicator. The cycle was repeated, and the resulting digested sample was transferred into a graduated vial bottle and dilute with 10 ml distilled water. A reverse agua regia procedure was adopted for the digestion of Teflon filters. The digested sample was analyzed for heavy metals of interest using an atomic absorption spectrophotometer.

2.2.4. Health Risk Assessment

Ingestion, inhalation, and dermal contact are the three principal ways that individuals are exposed to heavy metals in the air (Wang et al., 2018). This exposure assessment to heavy metals was computed and calculated for adults and children according to the Human Health Evaluation Manual (Part A), Supplemental Guidance for Dermal Risk Assessment (Part E), and Supplemental Guidance for Inhalation Risk Assessment (Part F) (Wang et al., 2018). The exposure assessment was calculated individually for ingestion (CDI), inhalation (EC), and dermal contact (DAD).

The formulas for calculation are shown in Equations (1), (2) and (3):

$$\text{Chemical daily ingestion}(\text{mg/kg})(\text{CDI}) = (\text{C} \times \text{IR} \times \text{EF} \times \text{ED} \times \text{CF})/(\text{BW} \times \text{AT}) \quad (1)$$

$$\text{Exposure concentration inhalation}(\text{g/m}^3)(\text{EC}) = (\text{C} \times \text{ET} \times \text{EF} \times \text{ED})/\text{ATn} \quad (2)$$

$$\text{Dermally absorbed dose}(\text{mg/kg})(\text{DAD}) = (\text{C} \times \text{SA} \times \text{AF} \times \text{ABS} \times \text{EF} \times \text{ED} \times \text{CF})/(\text{BW} \times \text{AT}) \quad (3)$$

Parameter	Notation	Unit	Value		
			Children	All ages	Adults
Metal concentration in $PM_{2.5}$	C	μg/m³		Table 2	
Average lifetime	ATn	hours		ED × 365 × 24 (for non-carcinogens) ED × 365 × 24 (for non-carcinogens) 70 × 365 × 24 (for carcinogens) 70 × 365 × 24 (for carcinogens)	
Average lifetime	AT	days		ED × 365 (for non-carcinogens) ED × 365 (for non-carcinogens) 70 × 365 (for carcinogens) 70 × 365 (for carcinogens)	
Body weight	BW	Kg		15.9 56.8	
Conversion factor	CF	mg/kg		10^{-6}	
Exposure duration	ED	Year		6 24	
Exposure frequency	EF	Days/year		350 350	
Exposure time	ET	h/day		24	
Ingestion rate	IR	mg/day		200 100	
Skin surface area adherence that contacts the airborne particulates	SA	cm²		1600 4350	
Skin adherence factor for the airborne particulates	AF	mg/cm²		0.2 0.07	
Dermal absorption factor	ABS	/		0.03 (As), 0.1 (Pb), 0.001 (Cd), 0.01 (other metals)	

LEGEND: Parameters for exposure assessment for adults and children defined for notation and units (source: Revised from Wang et al., 2018).

2.2.5. Risk Characterization of Heavy Metals in Air

A risk characterization assessment was undertaken to calculate the non-carcinogenic risk. The hazard quotient (HQ) assesses the non-carcinogenic risk of a particular pollutant in an exposure route (Wang et al., 2018). The non-carcinogenic hazard quotient (HQ) is computed as the quotient between the atmospheric exposure and the reference dose (RfD) (Koki et al., 2015). An HQ below one indicates a lower probability of non-carcinogenic side effects is less. A higher HQ indicates a higher probability of non-carcinogenic effects (Wang et al., 2018). The HQ was calculated using the method by Wang et al. (2018) in Equations (4), (5) and (6).

$$\text{Non-carcinogenic Hazard Quotient (HQ)} = CDI/RfDo \quad (4)$$

$$HQ = DAD/(RfDo \_ GIABS) \quad (5)$$

$$HQ = EC/(RfCi \_ 1000) \quad (6)$$

Legend (Source: Wang et al., 2018):

CDI - Chemical daily intake throμgh ingestion (mg/kg) (CDI),
EC - Exposure concentration throμgh inhalation (g/m^3) (EC),
DAD - Dermally absorbed dose (mg/kg) (DAD),
RfDo - oral reference dose (mg/kg/day),
RfCi - inhalation reference concentration (mg/m^3) *,
GIABS - gastrointestinal absorption factor* SFo - oral slope factor ((mg/kg/day) *.

2.3. Statistical Analysis

The data were analyzed using descriptive statistically significant and variance analysis (ANOVA). The ANOVA statistical difference was defined at $P < 0.05$ (Oguntoke et al., 2012). The correlation coefficient (r), 0.1 < /r/ < 0.3, signifies low correlation, while 0.3 < /r/ < 0.5 and /r/ > 0.5 signifies a moderate and strong correlation (Lala et al., 2023).

The sampling data at Ewekoro were validated with daily mean values of $PM_{2.5}$ from a 24-hour monitoring station at the University of Ibadan, Centre for Atmospheric Research, National Space Research and Development Agency (CAR-NASRDA). The pollutant levels are compared with Nigeria's National Environmental Standard and Regulation Enforcement Agency guideline (National Environmental Air Quality Control and Regulation, 2021), Canadian Ambient Air Quality Standards (CAAQS) (Canadian Council Ministers of the Environment, 2014) and World Health Organization (WHO).

An area map was created using Arc-GIS v10.3 to show the relationships between polluters and polluted areas. Maps or time series information were undertaken to represent the spatial and temporal variations in the concentration and dispersion of particulate matter and metal air pollutants. The method undertaken by Solademi & Thompson (2023) was undertaken using ArcGIS (Solademi & Thompson, 2023). The map was interpolated with geostatistical kriging analysis, and the green and yellow colour representations were used to show the level of the air quality zone as compared to the CAAQS. The interpolated maps used Green and red to show the WHO standards limit for heavy metals (Cd, Cr, Cu, Zn, Ni).

3. Results and Discussion

3.1. Mass Concentrations of Particulate Matters ($PM_{2.5}$ and PM_{10}) Near the Cement Factory

The mean PM concentrations in the cement factory (blasting/production area and packaging area), Papalantoro, Lapeleko and Itori are shown in **Table 2**. The daily concentration of $PM_{2.5}$ were highest at Itori 1 (18.48 μg/m^3), followed by the packaging area (PA2) (18.04 μg/m^3), and Papalantoro 1(17.24 μg/m^3). The cement factory pollution is near to neighbourhoods, with Itori being 4 km away, Palantoro 1km, Lapeleko 2 - 3 km and the Ewekoro sampling site 500 m - 2 km from the cement factory. For PM_{10}, the packaging areas had similar concentrations at 19.5 to 19.4 μg/m^3. Papalantoro has the highest daily concentration of (19.53 μg/m^3), followed by Itori 1 (19.47 (μg/m^3) and Blasting/production area (BPA1) (19.41 μg/m^3).

Table 2. Mean PM concentrations in ewekoro, papalantoro, lapeleko and itori.

Location	Daily mean $PM_{2.5}$ (μg/m³)	Daily mean PM_{10} (μg/m³)	Min Hourly $PM_{2.5}$ (μg/m³)	Max Hourly $PM_{2.5}$ (μg/m³)	Min Hourly PM_{10} (μg/m³)	Max Hourly PM_{10} (μg/m³)	Daily mean AQI (μg/m³)
Blasting/ production area (BPA1)	12.07	12.72	6.00	7.00	24.00	24.00	50.9
Blasting/ production area (BPA2)	11.71	12.53	7.00	7.00	20.00	21.00	48.8
Packaging area 1 (PA1)	16.39	19.41	7.00	7.00	68.00	72.00	59.72
Packaging area 2 (PA2)	18.04	19.24	7.00	8.00	72.00	75.00	61.74
Papalantoro 1	17.24	19.53	7.00	33.00	8.00	36.00	61.80
Papalantoro 2	12.82	13.17	5.00	30.00	5.00	31.00	52.80
Papalantoro 3	9.66	10.03	4.00	62.00	4.00	63.00	40.20
Lapeleko 1	7.67	8.65	4.00	15.00	5.00	16.00	32.10
Lapeleko 2	6.34	6.84	4.00	14.00	4.00	15.00	26.40
Lapeleko 3	13.58	14.65	4.00	54.00	6.00	57.00	54.10
Itori 1	18.48	19.47	8.00	59.00	8.00	63.00	64.40
Itori 2	13.89	14.36	5.00	32.00	5.00	32.00	54.80
24-hr NESREA guideline	40.00 μg/m3	150.00 μg/m3					
WHO guideline 2021	50.00 μg/m3						
24-hr CAAQS guideline	27.00 μg/m3						

The pollutant averages for each sample were averaged for each site to compare their pollutant levels. The daily mean $PM_{2.5}$ concentration was highest in the packaging area (PA2) (17.22 ± 1.17 μg/m³), which was closest to the cement factory (less than 500 meters). The lowest daily mean $PM_{2.5}$ concentration (9.20 ± 3.85 μg/m³) was recorded at Lapeleko, about 3 km from the factory, which, according to the windrose, was upwind of both the cement blasting and manufacturing operations that sampling day.

The minimum hourly concentration of $PM_{2.5}$ for all the monitoring sites ranges between 4 - 8 μg/m³, being very similar across the different sites. However, the maximum hourly concentration of $PM_{2.5}$ varies greatly, ranging from 7 - 62 μg/m³. Furthermore, the minimum hourly concentration of PM_{10} was between 4 - 72 μg/m³, while the maximum hourly concentration of PM_{10} ranged from 21 - 75 μg/m³. This study revealed that none of the locations exceeded the particulates 24-hr NESREA guideline of 40 μg/m³ for $PM_{2.5}$ and 150 μg/m³ for PM_{10}. These levels are below the levels reported by Bada et al. (2013) for this Ewekoro region, finding a $PM_{2.5}$ concentration of 76 μg/m³ and PM_{10} at 93 μg/m³ near this Lafarge factory. The levels we found at Ewekoro are also below the PM_{10} levels near cement factories in Indian cities of 100 - 400 μg/m³ (Sharma et al., 2003). The lower rates at this cement factory are explained by pollution prevention measures and limitations of sampling - sampling for eight hours despite a 24-hour operation at the cement factory.

Figure 4 shows the average 10-minute values of $PM_{2.5}$ at the CAR—NASRDA and the University of Ibadan monitoring stations for March 18th, 19th, and 20th, 2024, over the full 24-hour day. This time series data plot of $PM_{2.5}$ provides colour coding by the Air Quality Index values. Figure 4 shows the colour codes of acceptable levels in green, occurring mostly in the early morning and late afternoon, with worsening air quality from yellow to orange during the late night, peaking around midnight, and a second peak around noon. These reference sites never reached the red level.

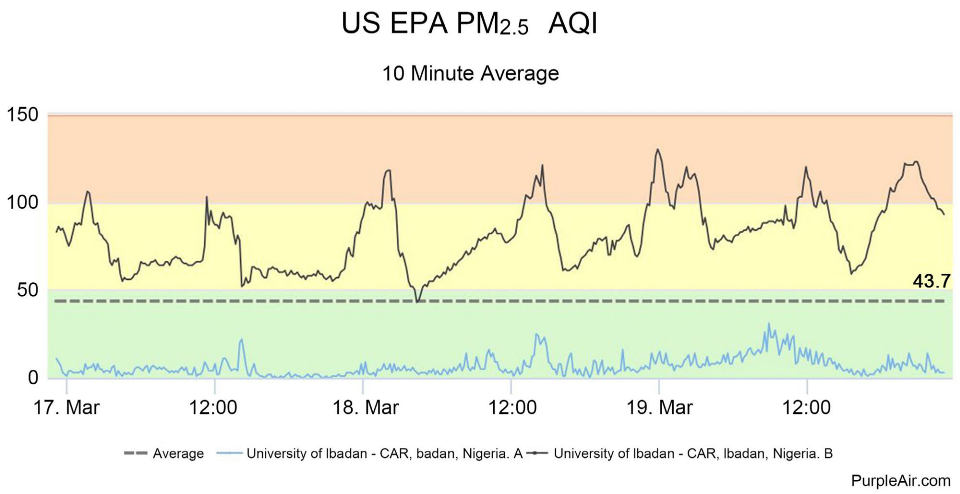


Figure 4. Average 10-minute concentrations of Respirable Particulate Matter ($PM_{2.5}$) and the Air Quality Index at different reference sites (Revised from CARNASRDA, 2024).

Figure 5 shows the respirable particulate levels at the Ewekoro Lafarge Cement Factory. The monitoring points are northwest to northeast for blasting/production area (BPA) measurements and southeast to southwest for packaging area (PA) measurements. The $PM_{2.5}$ levels in the packaging area (PA) appears similar to the blasting/production area (BPA), except for certain episodes, which could be during material delivery, batch operation, cleaning or other shorter-duration activity. On the first day of sampling, packaging area (PA1) had a peak at 9:00 a.m. of 40 μg/m³ and remained well below 20 μg/m³ until 12:30, reaching 30 μg/m³ at 2:30, 40 μg/m³ at 3:15 and almost 70 μg/m³ at 4:15. The second day of sampling packaging area (PA2) showed a large peak at 9:00 am above 90 μg/m³, with the pollution going up and down between 70 and 13 μg/m³ for the remainder of the day Blasting/production area values are much more constant, without sudden peaks, mainly hovering around 8 μg/m³ and 15 μg/m³.

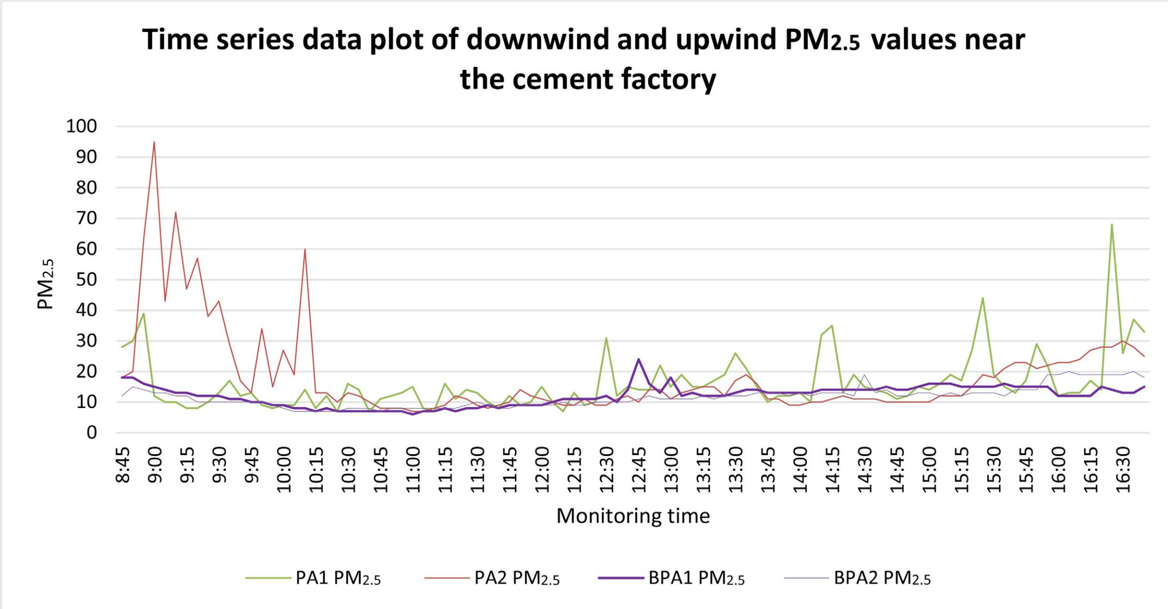


Figure 5. The hourly concentration of respirable particulate matter below 2.5 μg/m³ ($PM_{2.5}$) at the ewekoro lafarge cement factory.

The level at the packaging area sampling points surpasses the 25 μg/m³, and the level at the blasting/production area sampling points never surpassed the threshold level. The average value for $PM_{2.5}$ in the cement factory BPA and PA is 11.8 μg/m³ (variance of 9.4 μg/m³, standard deviation of 3.1 μg/m³) and 15.4 μg/m³ (variance of 28.9 μg/m³, standard deviation of 5.4 μg/m³) respectively. No statistically significant difference occurred between the blasting/production area (BPA) and packaging area (PA) means of $PM_{2.5}$, where (F = 3.156) and P-value = 0.097) using one-way ANOVA.

Exposure to respirable particulate matter aggravates lung disease, causes asthma and acute bronchitis and increases susceptibility to respiratory infections. The daily particulate means are below the regulatory levels. Figure 6 shows the daily $PM_{2.5}$ and PM_{10} mean values compared to regulatory standards. The PM_{10} μg/m³ levels were similar at the cement factory area and other neighbourhoods monitored and well below Nigeria's NESREA standard. The respirable particulate matter ($PM_{2.5}$ μg/m³) mean concentration at the blasting/production cement factory area are lower than in the packaging area. The $PM_{2.5}$ and PM_{10} mean concentrations are highest in the packaging area of the cement factory and lowest in the blasting/production area, which includes Lapeleko. The average value for $PM_{2.5}$ in the neighbourhood varies from 9.2 μg/m³ (variance of 14.8 μg/m³, standard deviation of 3.8 μg/m³) at Lapeleko to 16.1 μg/m³ (variance of 10.5, standard deviation of 3.2 μg/m³) downwind at Itoro as shown in Table 2 in the appendix. Trucks loaded with cement at the packaging area monitoring locations appeared to contribute to the higher values of $PM_{2.5}$ at this location. The Lapeleko $PM_{2.5}$ mean was slightly below the blasting /production area, as Lapeleko was directly upwind during monitoring.

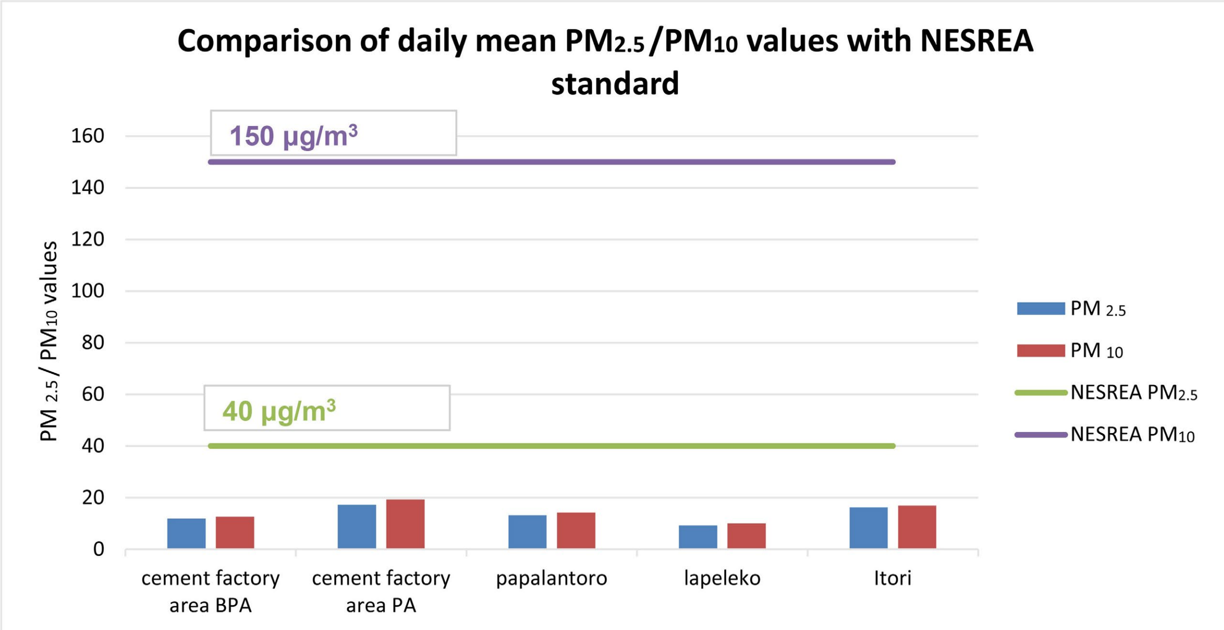
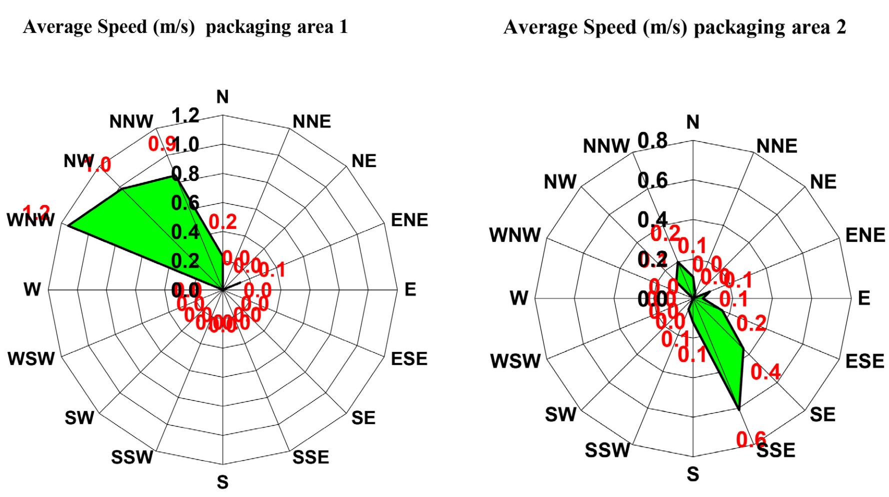


Figure 6. Daily particulate matter ($PM_{10}/PM_{2.5}$ μg/m^3) mean at different sampling sites compared to regulatory NESREA standard.

3.2. Wind Rose Plots

The direction in which the pollutant (particulate matter) travels is the result of the wind (George et al., 2008) and shifts with the wind. Wind rose plots were investigated for the different sampling locations to examine the effects of meteorological parameters on the dispersion of the particulate matter. Figure 7 shows wind speed and direction measured in the study area using a 16 radial arm wind rose (22.5˚) for data (Jurado et al., 2021) monitored from wind sensors placed 10 meters from the ground. The monitoring locations considered in this study give distinct but complementary information.



(a) (b)

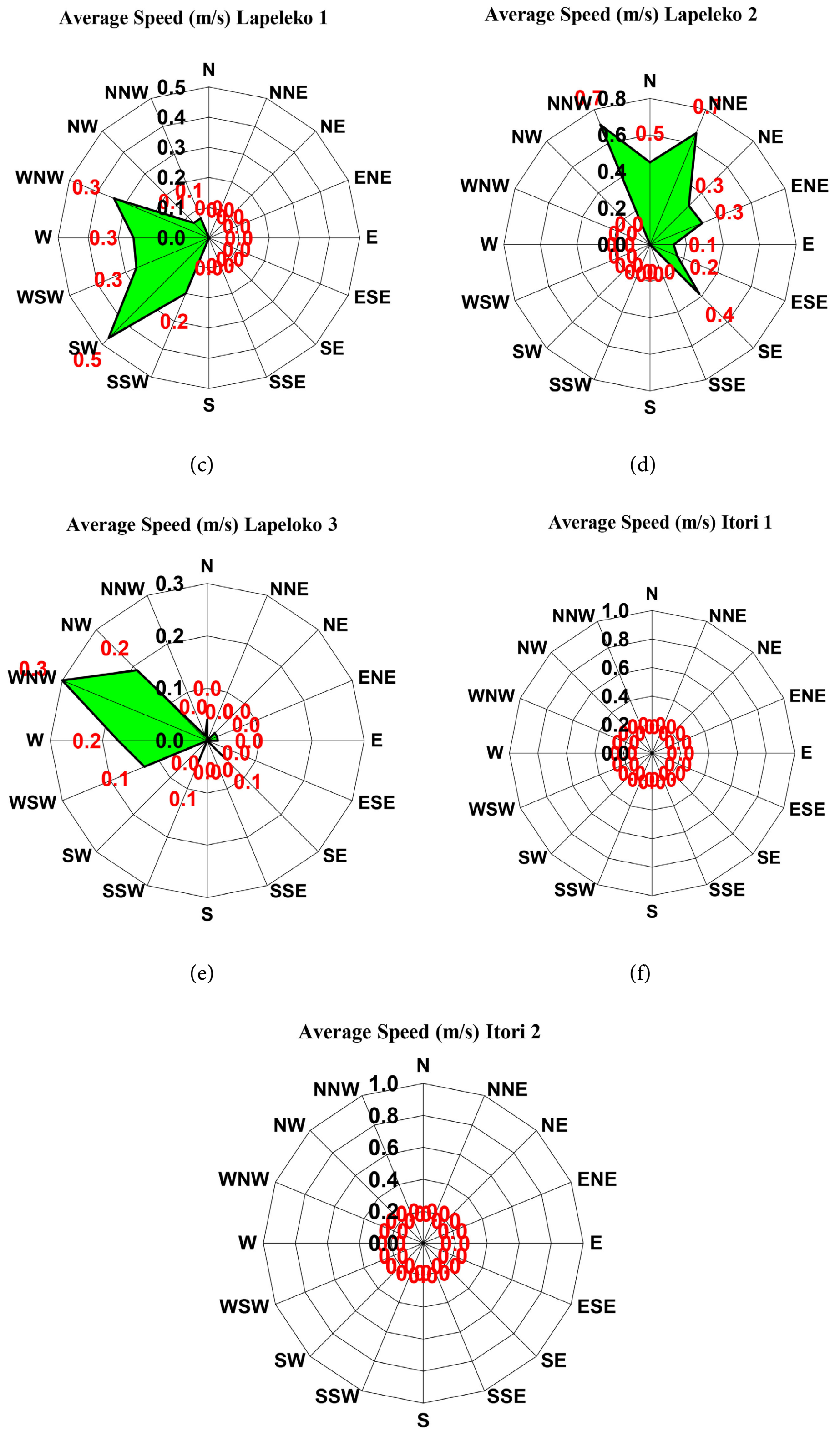


Figure 7. Average wind speed for the sampling days near the Ewekoro Lafarge cement factory. Source: Envirowave consulting, meteorological data for atmospheric modelling, 2024.

Figure 7 shows that the wind was low-speed during most sampling near the cement factory. Higher velocities occurred during the sampling of the packaging area (PA1). However, most monitoring days had velocities hovering near Itori, the closest neighbour to the cement factory on the northeast side, the lack of wind on both monitoring days allowed pollution to build up around the plant and in Itori. Itori was not downwind of the cement factory or the blast areas, but when the weather is calm, the pollution tends to linger in the nearby vicinity and put people at risk.

3.3. Air Quality Index Near the Ewekoro Lafarge Cement Factory

The Air Quality Index (AQI) provides important information on the health of the air based on pollutant levels. (Lala et al., 2023). The AQI details the potential health dangers of breathing in polluted air and any side effects that can appear hours or days later. A lower AQI value is considered better-quality air.

The daily mean ± SD in the study area was applied to the AQI. These levels were Blasting area/production area (49.85 ± 1.48 μg/m^3), Cement packaging area (60.73 ± 1.43 μg/m^3), Itori (59.60 ± 6.79 μg/m^3), Papalantoro (51.60 ± 10.85 μg/m^3) and Lapeleko (37.53 ± 14.63 μg/m^3) as shown in Table 1 in the appendix. The AQI levels were worse closer to the cement factory when downwind. The daily mean AQI was highest at Itori 1 (64.4 μg/m^3).

3.4. The Risk Assessment of $PM_{2.5}$ in the Cement Factory Area and Impacted Neighbourhoods

The risk assessment of $PM_{2.5}$ in the cement factory area and impacted neighbourhoods was evaluated using the Canada Ambient Air Quality Standards (Canadian Council Ministers of the Environment, 2014). This study applied the 27 μg/m^3 24-hour CAAQS guideline for $PM_{2.5}$, as shown in Table 3 in the appendix. The highest daily mean value of $PM_{2.5}$ in the cement factory area was 18.04 μg/m^3 which was below the 24-hour CAAQS guideline. However, for air quality management, this value falls in the yellow colour category of the CAAQS guideline of 11 μg/m^3 to 19 μg/m^3, which implies continuous actions are needed to improve air quality in the cement factory area. The highest daily mean values of $PM_{2.5}$ at Papalantoro, Lapeleko and Itori are 17.24 μg/m^3, 13.58 μg/m^3, and 18.89 μg/m^3 respectively. These values are below the CAAQS of 27 μg/m^3 but also fall in the yellow colour category of CAAQS guideline $PM_{2.5}$ values between 11 μg/m^3 to 19 μg/m^3 in the air quality management level.

Figure 8 shows the spatial distribution of $PM_{2.5}$. All areas are below the WHO standards, and so this diagram shows the CAAQ standards. Figure 8 shows that the level of $PM_{2.5}$ for Itori 1 and all samples for Papalantoro is satisfactory for the CAAQs standard, shown in green. The $PM_{2.5}$ concentration for Lapeleko, the Ewekoro Lafarge Cement Factory blast and packing areas, falls above 10, signified by yellow on the map. Thus, these areas need continuous action to improve air quality, according to CAAQS.

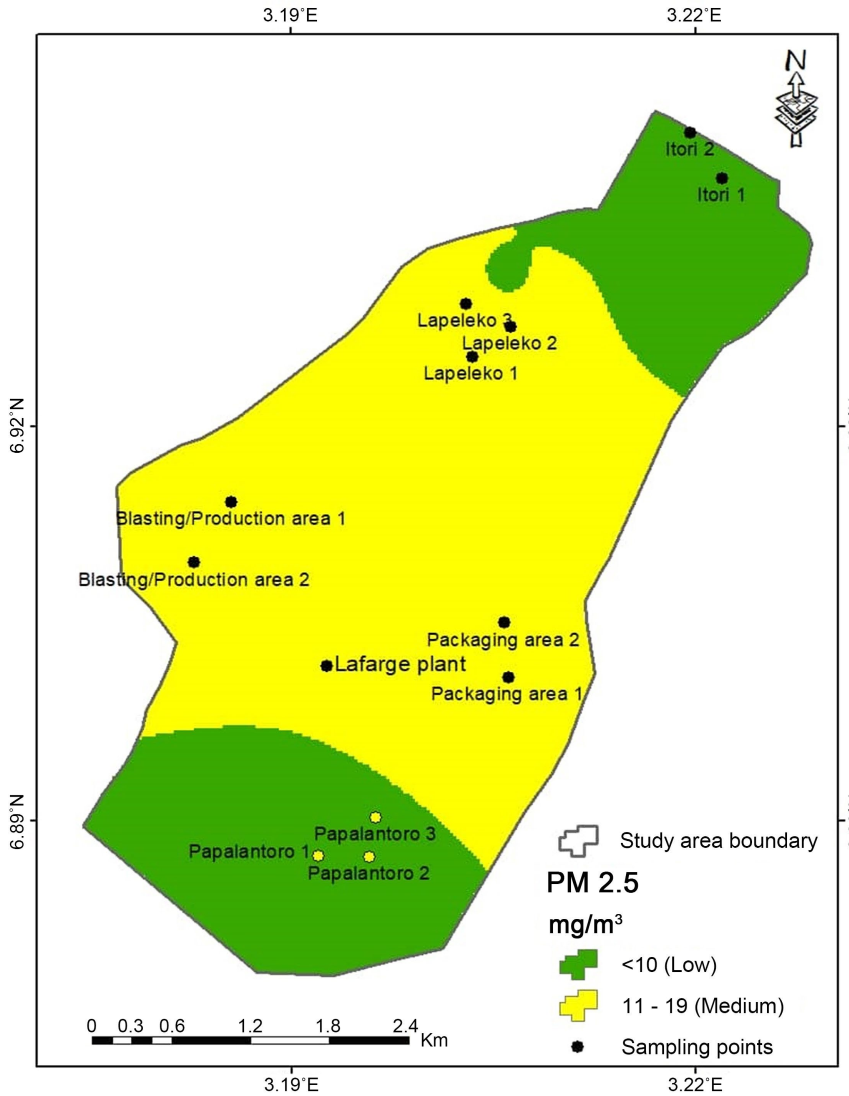


Figure 8. Spatial distribution of $PM_{2.5}$ in the Ewekoro Lafarge Cement Factory area and the neighbourhoods sampled.

3.5. Concentration of Heavy Metals

Cement production elevates the concentration of heavy metals in the surrounding environment (Abimbola et al., 2007). **Table 3** shows that the different heavy metal concentrations in the particulate air samples vary across the cement factory area, Papalantoro, Lapeleko, and Itori. However, a noticeably higher level of most heavy metals was found in the cement factory's blasting area, packaging area, and nearby neighbourhoods of Papalantoro and Lapeleko.

Heavy metals are dangerous pollutants that can build up in human tissues (Leili et al., 2008). Cadmium (Cd) was not detected in most locations. However, higher concentrations of Cd (0.03 mg/m^3) were observed in PA1. The harmful effects of Cd include carcinogenicity, mutagenicity, disruption of the endocrine system, fragile bones (osteoporosis), and impairment of lungs and kidneys, among other biological disorders (Bandow & Simon, 2016; Oguntade et al., 2020).

Table 3. Levels of heavy metals in the particulate air samples near the Ewekoro Lafarge Cement Factory.

Location	Cd mg/m^3	Cr mg/m^3	Cu mg/m^3	Ni mg/m^3	Pb mg/m^3	Zn mg/m^3
Blasting/ production area (BPA1)	0.009	1.579	0.024	0.424	Nd	0.136
Blasting/ production area (BPA2)	Nd	2.033	0.036	0.601	Nd	0.019
Packaging area (PA1)	0.032	2.608	Nd	0.836	Nd	0.254
Packaging area (PA2)	Nd	0.985	Nd	0.795	Nd	Nd
Papalantoro 1	0.013	2.710	0.054	0.201	Nd	0.203
Papalantoro 2	Nd	0.535	Nd	0.259	Nd	Nd
Papalantoro 3	Nd	2.672	0.090	1.306	Nd	0.053
Lapeleko 1	Nd	1.254	Nd	0.990	Nd	Nd
Lapeleko 2	Nd	1.836	Nd	1.133	Nd	Nd
Lapeleko 3	Nd	2.116	0.150	1.133	Nd	0.011
Itori 1	Nd	0.716	0.204	1.414	Nd	Nd
Itori 2	Nd	1.138	Nd	1.495	Nd	0.111
WHO Limit	0.005	1.000	1.000	0.050	0.050	5.000

Legend: nd = not detected, Red numbers indicate levels higher than the WHO limit.

All samples contained Chromium (Cr). Some Cr comes from the limestone and clay materials used to manufacture cement. During the clinkerisation process chromate (Cr(III)) can partly oxidize to turn to Cr(VI), which is allergenic. The linings for the rotaries in cement factories contain Cr. The rotary friction causes wear and tear on the linings, which release into the air (Banat et al., 2005; Okoro et al., 2017). Malignancies of the lung, kidney failure, heart attack, bronchial cancer, prostatic proliferative lesions, and fractures in the bones are among the long-term consequences of cadmium exposure (Ayua et al., 2020). Chromium ulcers, acidic reactions on the septum of the nasal cavity, allergic eczematous skin irritation, and acute irritative dermatitis are associated with substances containing chromium(VI) (Leili et al., 2008).

Nickel(Ni) is present at high levels in cement in a non-water soluble form. Overexposure to Ni may result in skin irritation, such as irritating hands and other areas (Ayua et al., 2020). Elevated Ni levels are linked to asphyxia, convulsions, and digestive issues. Chronic exposure can cause headaches, light-headedness, weakness, memory loss, hair loss, chest tightness, sleeplessness, and reduced libido. All samples had Ni at levels that exceeded WHO standards. Some samples exceeded the levels by almost 30 times, reaching 1.5 compared to 0.05 mg/m^3. The highest concentration of Ni was observed in Itori 2 at 1.5 mg/m^3, respectively. Nickel exposure causes lung and nasal cancers (Ayua et al., 2020).

Most heavy metal levels near the Ewekoro Lafarge Cement Factory exceeded the WHO standard. Chromium (Cr) had the highest concentration of 2.71 mg/m^3 at Papalantoro 1, followed closely by Papalanto 3 with 2.67 mg/m^3. The heavy metals' mean concentration (mg/m^3) and standard deviation were calculated. The mean levels were Cd (0.01 ± 0.02 mg/m^3), Cr (1.80 ± 0.522 mg/m^3), Cu ((0.02 ± 0.02 mg/m^3), Ni (0.66 ± 0.21 mg/m^3), and Zn (0.10 ± 0.12 mg/m^3) for the cement factory area (BPA and PA). Several chemicals did not exceed the WHO levels for any sample. These chemicals were Cu, Pb and Zn. Lead (Pb) was not detected in any sample. The levels of Zn were highest at packaging area sampling points of the cement factory at 0.25 mg/m^3, followed by Papalantoro 1 at 0.20 mg/m^3.

Figure 9 compares the heavy metal concentrations (mg/m^3) in the air at the Ewekoro Lafarge Cement Factory and nearby neighbourhoods. The cement factory area, Palantoro, Lapeleko, and Itori, has visibly higher chromium and nickel concentration levels. The concentrations of Cd in all the areas monitored were lower.

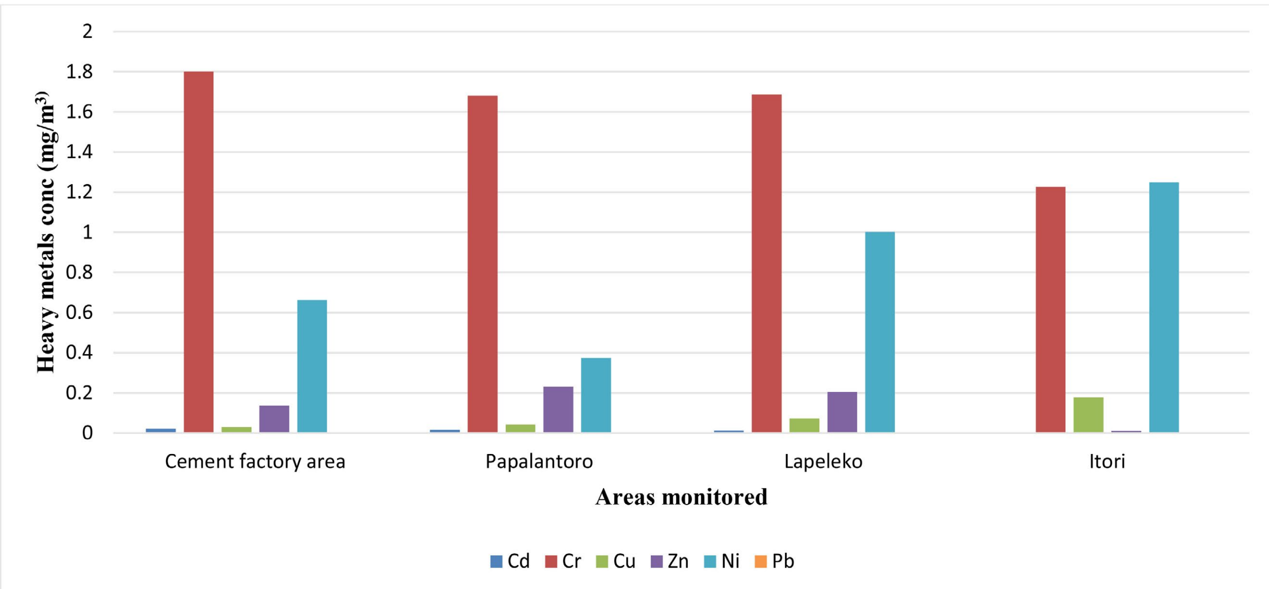
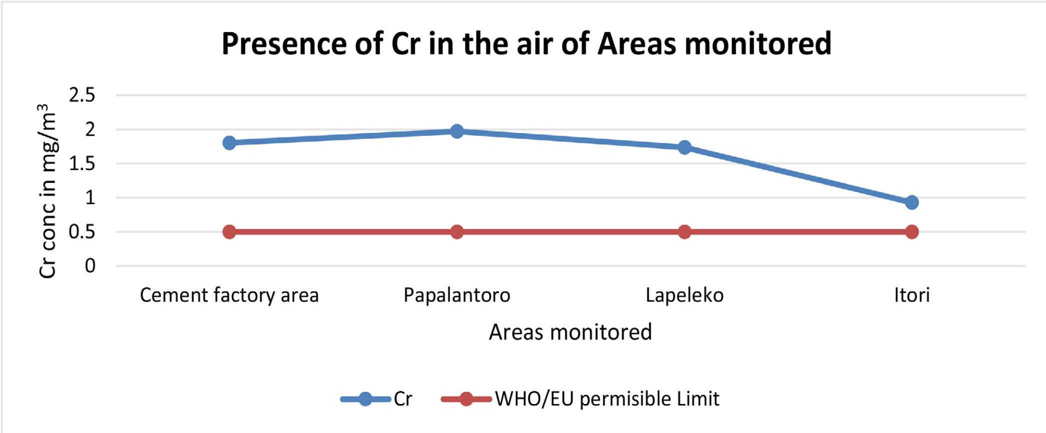


Figure 9. The heavy metal air concentrations (mg/m^3) at the Ewekoro Lafarge Cement Factory and nearby neighbourhoods.

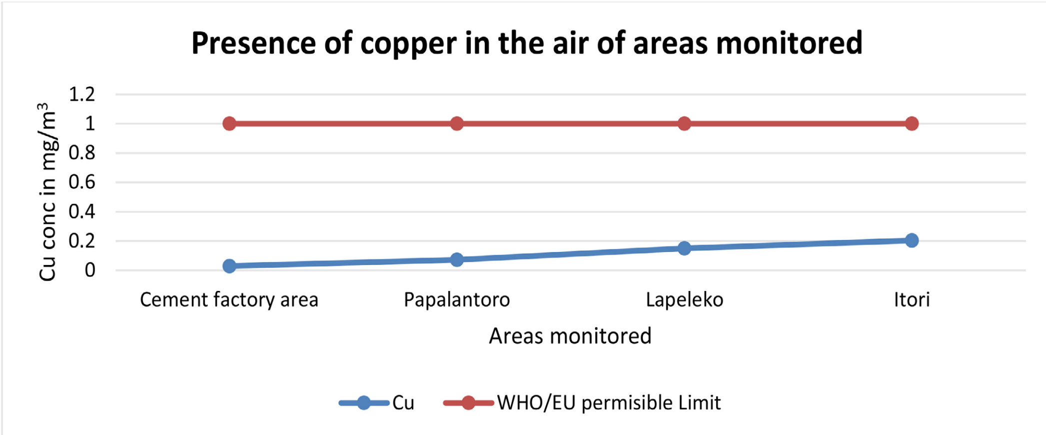
Figures 10(a)-(e) show the levels of heavy metal concentrations in all the areas monitored compared with the WHO/EU permissible limit. Cadmium, nickel, and chromium levels are higher than the WHO/EU permissible limit, while zinc and copper levels are lower.

3.6. Correlation of Blasting/Production Area to Packaging Area $PM_{2.5}$ Concentrations

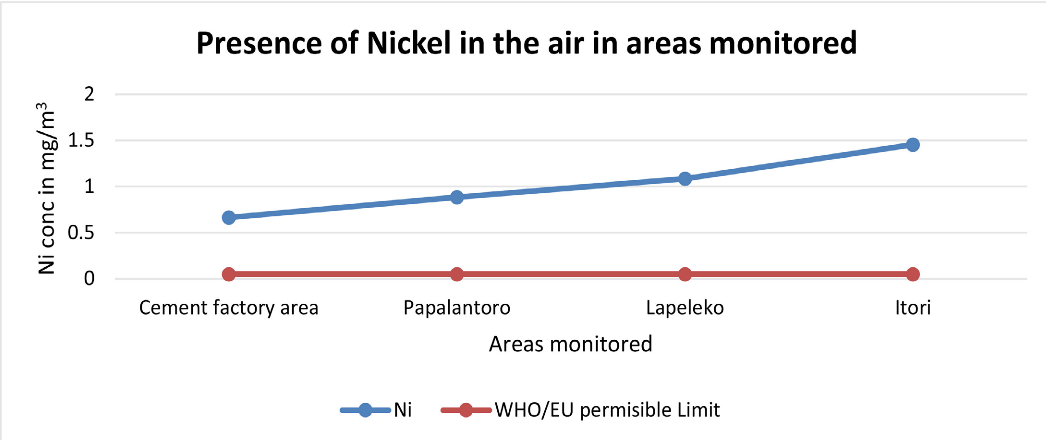
Figure 11 shows the relationship between the hourly values of $PM_{2.5}$ in the blasting area and the packing area at Ewekoro's Lafarge Cement factory. The moderate correlation (r = 0.458) between them indicates similar pollutants from similar sources (Lala et al., 2023). A linear relationship between the hourly values of $PM_{2.5}$ between the blasting area and the packing area at Ewekoro's Lafarge Cement factory.



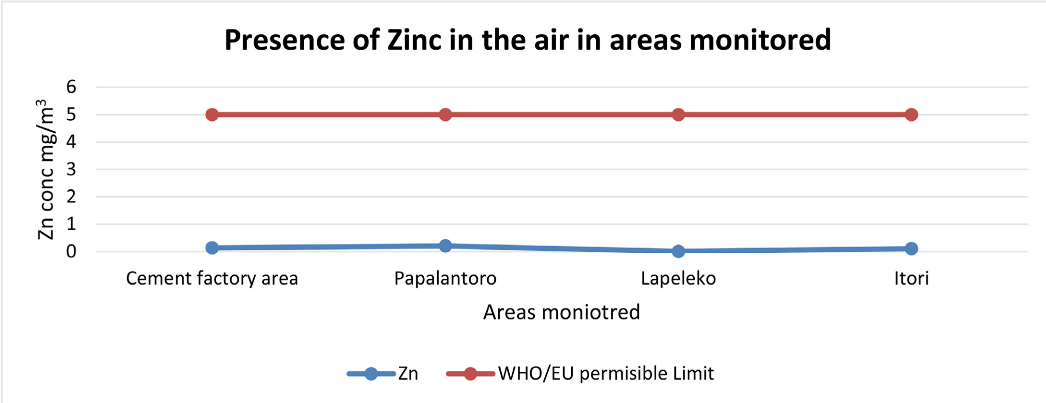
(a)



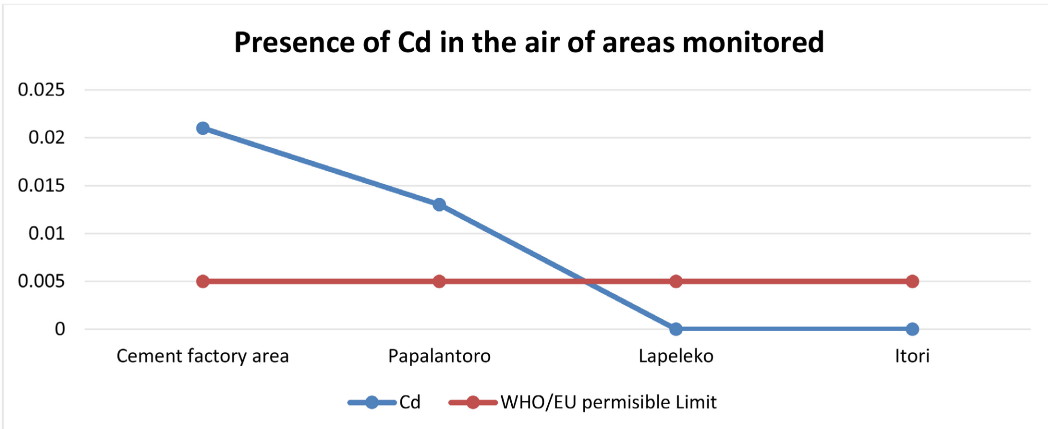
(b)



(c)



(d)



(e)

Figure 10. (a)-(e) Heavy metal concentrations around the cement factory and impacted neigbourhoods compared with the WHO/EU permissible limit.

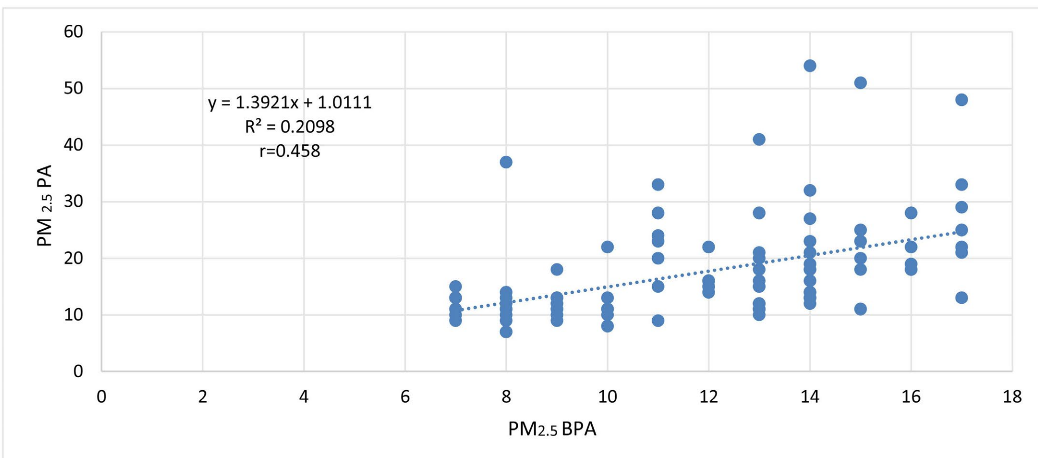


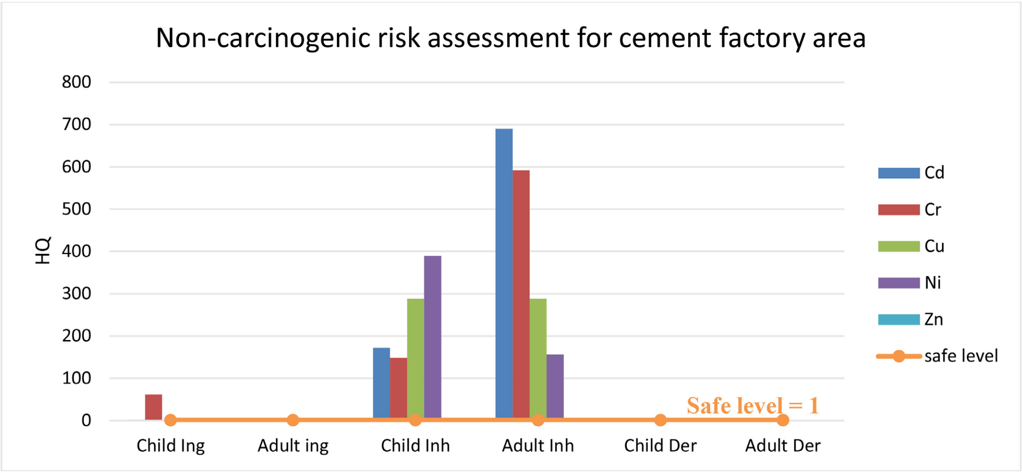
Figure 11. Correlation between $PM_{2.5}$ blasting/production area and the Ewekoro Cement Factory packaging area in Nigeria.

3.7. Non-Carcinogenic Risks Assessment of Heavy Metals in the Air

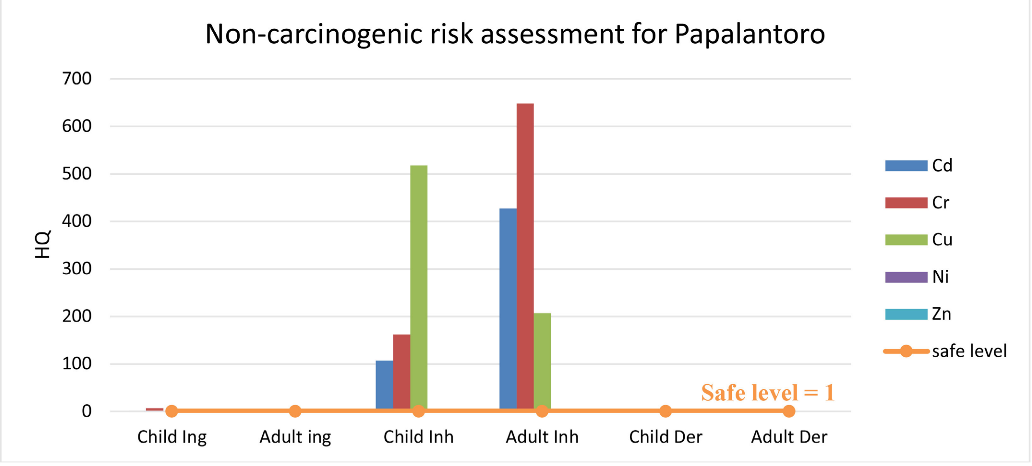
Figures 12(a)-(d) show the exposure and non-carcinogenic risks assessment

(HQ) of the heavy metals at the Ewekoro Lafarge factory and the impact on the neighbourhoods—Papalantoro, Lapeleko, and Itori. This HQ considered children and adults throμgh ingestion, inhalation, and dermal contact. A HQ higher than the safe level (=1) signifies the potential non-carcinogenic effects on the community members. A HQ lower than the safe level signifies no significant non-carcinogenic effects to residents (Wang et al., 2018).

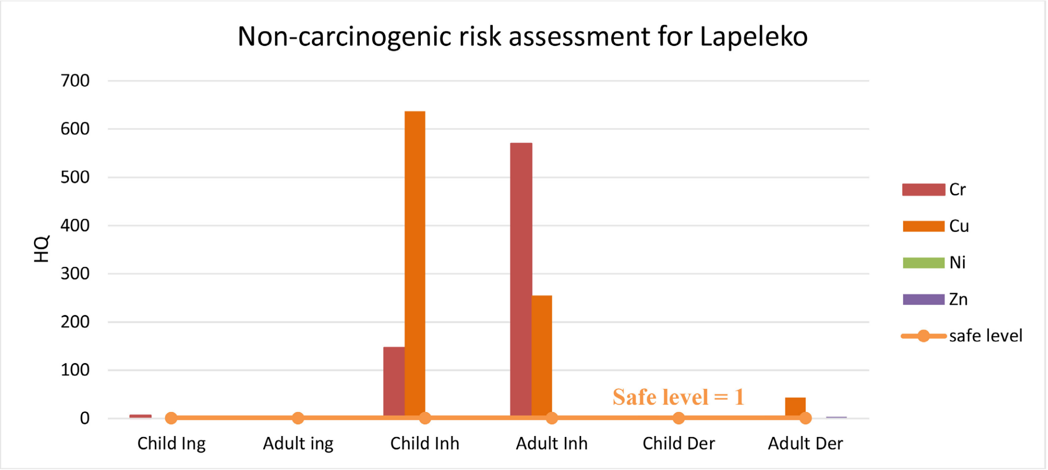
Figures 13(a)-(e) show the spatial distribution of heavy metals (Cadmium Chromium, Copper, Nickel and Zinc) at Ewekoro Lafarge cement factory and the and impact on nearby neighbourhoods. Figure 13(b) and Figure 13(c) show Zn and Cu concentrations in all locations monitored. The concentration of Zn and Cu falls in the low-risk category below the WHO/EU threshold level. The concentration of Cr in the air was higher than the WHO threshold level in most locations sampled, as indicated in Figure 13(d). The concentration of Cd was higher than the WHO threshold level at some sampling locations near the cement factory area and impacted neighbourhoods, and it was low in other locations monitored. The concentration of Cr was high in most of the locations monitored.



(a)



(b)



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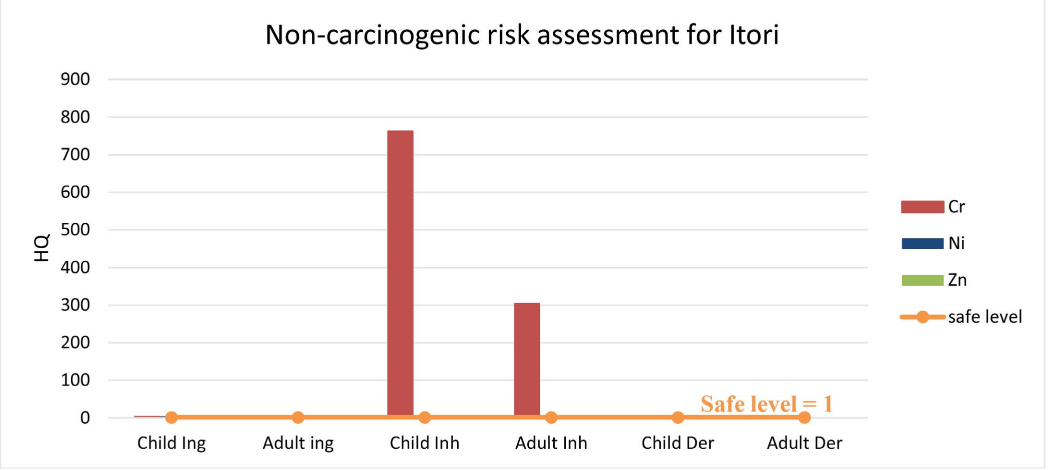


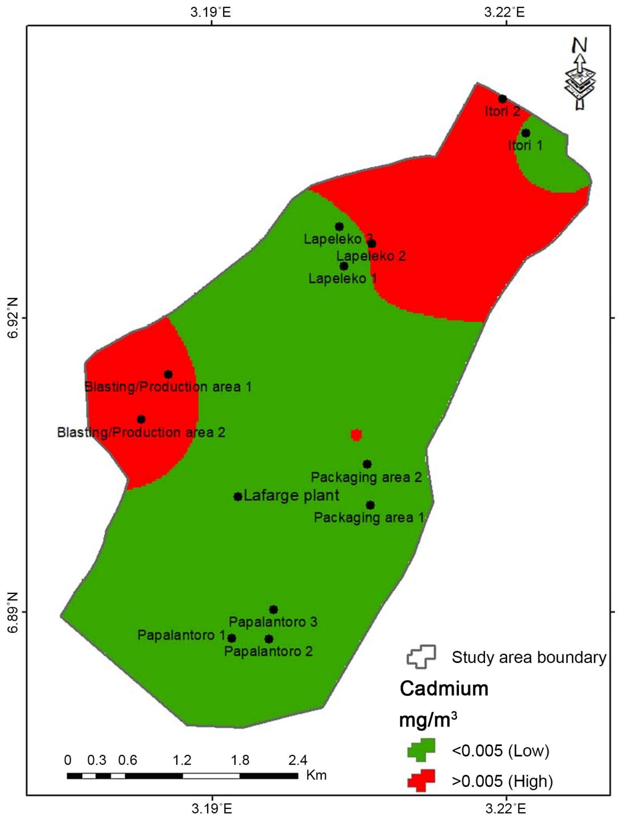
(d)

Figure 12. (a)-(d) The non-carcinogenic risk assessment of heavy metals in the air of the areas monitored.

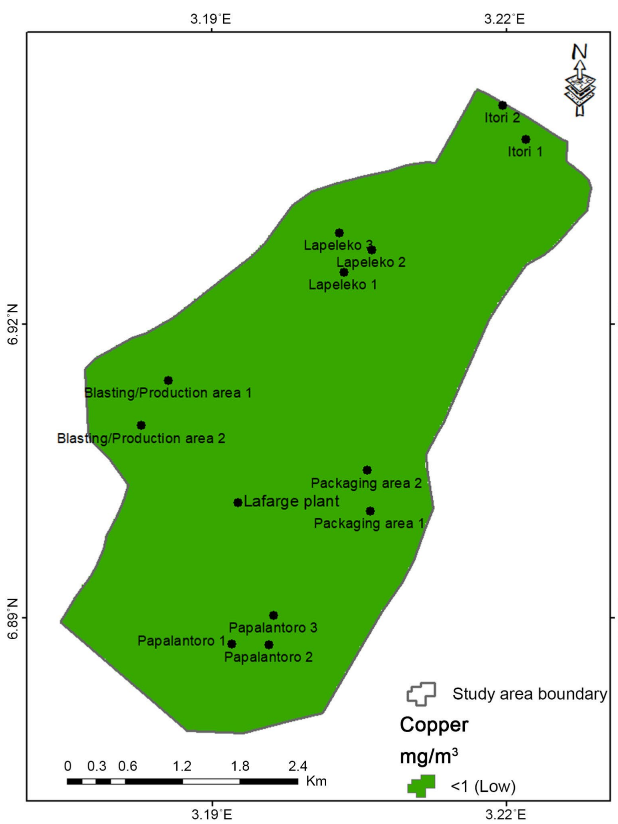
4. Conclusion

An exposure risk assessment was made through sampling for $PM_{2.5}$, PM_{10}, and heavy metals at the Ewekoro cement factory and surrounding neighbourhoods in Nigeria. Higher pollutant levels were noticed at the cement factory, pointing to it as a source of pollution. The Lapeleko neighbourhood had fewer respirable PM and heavy metal concentrations.

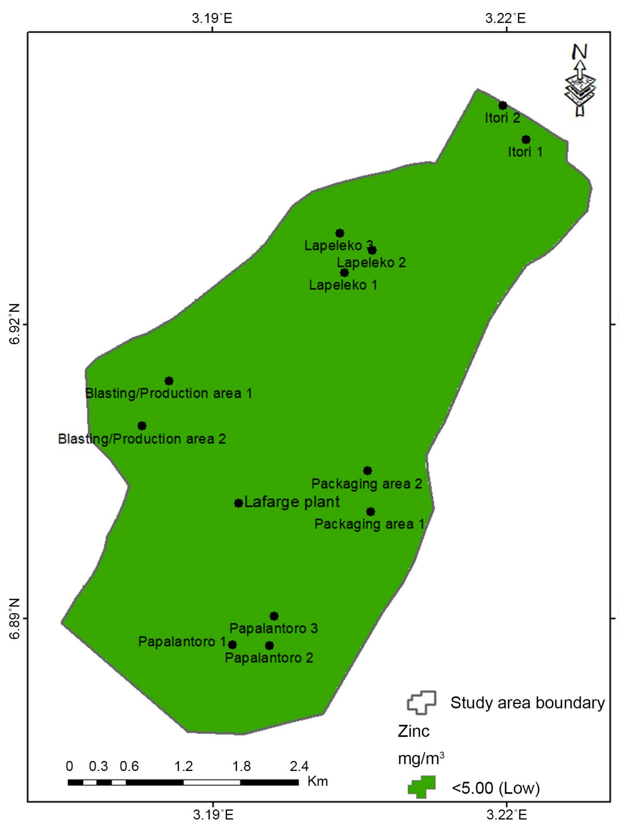
The large concern was the high concentration of heavy metals in the particulate matter samples. Heavy metals were found in all the samples. The mean concentrations of Cd, Cr, and Ni in the cement factory vicinity and the impacted neighbourhood are higher than the WHO/EU permissible limits. These high levels increase both risks for cancer and non-carcinogenic risks. The non-carcinogenic risks are elevated in some areas for Cr, Ni and Cd. The hazard quotient (HQ) for Cr in the air of all the locations monitored was above the WHO/EU safe level (=1) in adults and children through ingestion, inhalation and dermal contact. Also, the HQ for Ni and Cd for some locations monitored was higher than the safe level.


3.19˚E
3.22˚E
6.92˚N
6.89˚N
N
Itori 2
Itori 1
Lapeleko 3
Lapeleko 2
Lapeleko 1
Blasting/Production area 1
Blasting/Production area 2
Packaging area 2
Lafarge plant
Packaging area 1
Papalantoro 3
Papalantoro 1
Papalantoro 2
Study area boundary
Cadmium
mg/m³
<0.005 (Low)
>0.005 (High)
0 0.3 0.6 1.2 1.8 2.4
Km

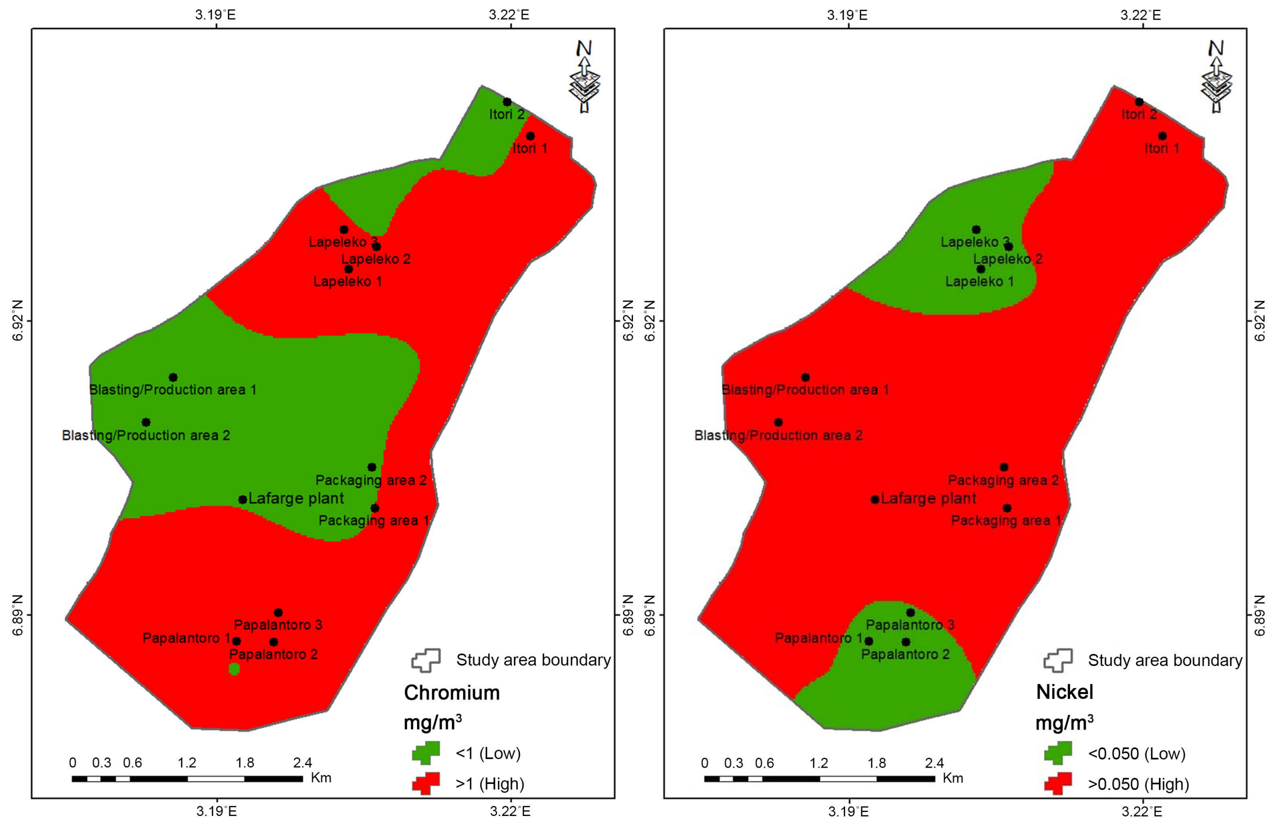
(a)


3.19˚E
3.22˚E
6.92˚N
6.89˚N
N
Itori 2
Itori 1
Lapeleko 3
Lapeleko 2
Lapeleko 1
Blasting/Production area 1
Blasting/Production area 2
Packaging area 2
Lafarge plant
Packaging area 1
Papalantoro 3
Papalantoro 1
Papalantoro 2
Study area boundary
Copper
mg/m³
<1 (Low)
0 0.3 0.6 1.2 1.8 2.4
Km

(b)


3.19˚E
3.22˚E
6.92˚N
6.89˚N
N
Itori 2
Itori 1
Lapeleko 3
Lapeleko 2
Lapeleko 1
Blasting/Production area 1
Blasting/Production area 2
Packaging area 2
Lafarge plant
Packaging area 1
Papalantoro 3
Papalantoro 1
Papalantoro 2
Study area boundary
Zinc
mg/m³
<5.00 (Low)
0 0.3 0.6 1.2 1.8 2.4
Km

(c)



(d) (e)

Figure 13. (a)-(e). Spatial distribution of heavy metals in the Ewekoro Lafarge Cement Factory area and the impacted neighbourhoods for (a) Cadmium (b) Chromium (c) Copper (d) Zinc.

Thus, significant non-carcinogenic Cr, Ni and Cd risks for children and adults occur around the cement factory.

The respirable particulate matter levels were below regulatory levels. The concentrations of PM_{10} in all the locations monitored were below the NESREA standard for 24 hours of 150 µg/m^3. The $PM_{2.5}$ was below the CAAQS regulation of 24 hours at 27 µg/m^3. However, most of the $PM_{2.5}$ results obtained in this study fall in the medium level range of 11 - 19 µg/m^3, which for CAAQS indicates that continuous actions are needed to improve air quality in the areas monitored.

This study's particulate matter, heavy metals concentration, and exposure risk assessments to human health provide useful information for policymakers and environmental regulators to reduce risk. The findings call for implementing air pollution control management, considering Cr, Ni, and Cd impacts. These findings should assist enforcement agencies in taking preventative action, highlighting the need for stricter regulations on air pollution.

Author Contributions

Conceptualization, Awos, Thompson & Adedeji; methodology, Awos & Thompson; validation, Thompson; fieldwork/data collection, Adedji & Taiwo; draft writing, Awos; writing - review and editing, Awos, Thompson, Adedji, Zymova, Zhang; supervision, Thompson.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Table A1. Air quality objectives and management level with a 24-hour-ranging concentration of PM2.5 (Canadian Council Ministers of the Environment, 2014).

Location	Monitoring Dates	Daily mean AQI (μg/m³)
Blasting/production area (BPA1)	20/03/2024	50.9
Blasting/production area (BPA2)	21/03/2024	48.8
Packaging area (PA1)	13/03/2024	59.7
Packaging area (PA2)	19/03/2024	61.7
Papalantoro 1	11/03/2024	61.8
Papalantoro 2	12/03/2024	52.8
Papalantoro 3	05/04/2024	40.2
Lapeleko 1	25/03/2024	32.1
Lapeleko 2	26/03/2024	26.4
Lapeleko 3	27/03/2024	54.1
Itori 1	08/04/2024	64.4
Itori 2	09/04/2024	54.8

Table A2. One-Way Analysis of Variance (ANOVA) of PM2.5 in the Cement Factory Area.

Groups	Count	Sum	Average	Variance
Packaging area (PA)	8	123.5	15.44	28.89
Blasting/production area	8	94.5	11.81	9.42

Source of Variation	SS	df	MS	F	P-value	F crit
Between groups	52.5625	1	52.5625	3.155722	0.097389	4.60011
Within groups	233.1875	14	16.65625			
Total	285.75	15				

$P < 0.05$.

Table A3. Air quality management level explained using different colour categories with CAAQS guidelines. (Revised from Canadian Council Ministers of the Environment, 2024).

Management Level	$PM_{2.5}$ 24-hour (μg m⁻³)	
	2015	2020
Red (CAAQS)	>28	>27
Orange	20 to 28	20 to 27
Yellow	11 to 19	11 to 19
Green	≤10	≤10

Table A4. Air quality management level explained using different colour categories. (Revised from Canadian Council Ministers of the Environment, 2014).

Management Level	Air quality objective
Green	To maintain good air quality throμgh proactive air management measures to keep clean areas clean.
Yellow	To improve air quality using early and ongoing actions for continuous improvement.
Orange	To improve air quality throμgh active air management and prevent exceedance of the CAAQS.
Red	To reduce pollutant levels below the CAAQS throμgh advanced air management actions.