Journal of Air Pollution and Health (Summer 2026); 11(3): 395-410

Original Article

Available online at https://japh.tums.ac.ir

Health risk assessment of the nexus between concurrent exposures to radon gas and particulate matter in resident buildings near cement factory

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ARTICLE INFORMATION

Article Chronology:
Received 24 January 2026
Revised 19 July 2026
Accepted 10 August 2026
Published 29 September 2026

Keywords:
Indoor air pollution; Particulate matter ($PM_{2.5}$ and PM_{10}); Radon; Cement production; Health risk assessment; Alpha track detection

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ABSTRACT

Introduction: Indoor air pollution is a growing public health concern, particularly in communities near industrial operations. This study evaluated indoor concentrations of fine and coarse Particulate Matter ($PM_{2.5}$ and PM_{10}) and radon in residential buildings located near cement factories in a selected town in Ogun State, Nigeria. The primary aim of this study was to investigate the concurrent indoor exposure to $PM_{2.5}$ and PM_{10} and radon gas in residences near cement manufacturing facilities, quantify the associated non-carcinogenic and carcinogenic health risks, and examine the correlation between these co-occurring pollutants.

Materials and methods: Air quality measurements were carried out in 20 residential buildings near cement plants. $PM_{2.5}$ and PM_{10} levels were measured using the Elitech Temtop LKC-1000S+ air quality monitor, while indoor radon concentrations were assessed with CR-39 solid-state nuclear track detectors. Particulate matter sampling was conducted twice daily over 30 consecutive days, while CR-39 detectors were deployed for a 30-day exposure period. Health risk evaluations followed standard models for both non-carcinogenic and carcinogenic assessments. Correlation analysis was conducted to examine the relationship between particulate matter and radon.

Results: Mean indoor concentrations of $PM_{2.5}$ and PM_{10} were 39.94 μg/m³ and 60.83 μg/m³, respectively, both above WHO limits. Radon concentrations averaged 92.48 Bq/m³, with 40% of sampled homes exceeding the WHO recommended level of 100 Bq/m³. Hazard quotients for $PM_{2.5}$ ranged from 2.3 to 3.0 and for PM_{10} from 1.0 to 1.5, yielding an average hazard index of 3.89. Elevated annual effective doses and excess lifetime cancer risks were also associated with radon. A positive correlation was found between particulate matter and radon levels.

Conclusion: The study reveals a significant combined health risk from PM and radon exposure in homes near cement factories. Targeted mitigation, improved regulation, and public health awareness are urgently needed to reduce exposure and protect residents.

Please cite this article as:, Dosunmu OG, Ademola AK, Olowofila I, Abodunrin PO, Funso Aina B. Health risk assessment of the nexus between concurrent exposures to radon gas and particulate matter in resident buildings near cement factory. Journal of Air Pollution and Health. 2026;11(3):395-410.
Doi: https://doi.org/10.18502/japh.v11i3.22627

Introduction

Indoor air quality influences human health, particularly due to the amount of time people spend inside buildings. Although residential environments are assumed to be safe, they can expose occupants to airborne pollutants from both indoor sources and outdoor contaminants that infiltrate through openings. In industrial regions, especially in areas close to cement factories, particulate matter from the surrounding environment frequently enters indoor spaces, resulting in elevated exposure levels [1, 2]. The World Health Organization identifies several contributors to indoor air pollution, including emissions from outdoor sources, internal pollutant generation, poor ventilation, and moisture accumulation. Inadequate airflow and damp conditions can further degrade indoor air quality [3]. Adults typically spend approximately 90 percent of their time indoors, thereby increasing their exposure to pollutants linked with respiratory and cardiovascular conditions, and in some cases, lung cancer [3, 4]. Of particular concern are fine and coarse particulate matter, specifically $PM_{2.5}$ and PM_{10}, along with radon gas. These pollutants are significant in residential zones situated near limestone quarries and cement production facilities. $PM_{2.5}$ and PM_{10} are microscopic airborne particles capable of penetrating deep into the respiratory tract. Research has associated their presence with asthma, chronic bronchitis, heart disease, and premature mortality [2, 5, 6]. Cement production contributes to airborne particulate matter through grinding processes, material transport, and kiln operations. Air pollution from such sources is estimated to cause approximately 3.2 million premature deaths globally each year [7].

Radon is a radioactive gas generated by the natural decay of uranium found in soil and rock formations [8, 9]. It enters homes through gaps in foundations and is influenced by geological characteristics, the type of building structure, and the efficiency of ventilation systems [10]. Although radon is inert in its gaseous form, it can bind to airborne particles such as carbon dioxide that is released during the calcination of limestone in cement kilns. This process allows radon to be carried into indoor environments. When radon gains entrances into an indoor environment, it undergoes radioactive decay, releasing short-lived progeny (such as ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) that either attach to existing airborne particles or remain as small unattached clusters with diameters ranging from approximately 0.5 to 300 nm [11–13]. These radioactive particles, when inhaled, can lodge in the lungs, emit alpha radiation, and increase the risk of lung cancer [14, 15]. Indoor radon concentrations can range widely from a few units to over 10,000 becquerels/m^3, depending on building design and location-specific factors [16, 17].

Although previous studies have primarily focused on how cement manufacturing affects outdoor air quality, limited research has investigated its effect on indoor environments. Existing findings indicate that emissions from cement activities such as material crushing, blending, and fuel combustion significantly raise surrounding concentrations of $PM_{2.5}$ and PM_{10} [18, 19].

Residential buildings, particularly those with structural flaws or inadequate ventilation, are especially vulnerable to the infiltration of environmental pollutants. In communities near cement manufacturing facilities, this risk is heightened. Raw materials commonly used in cement production, such as limestone and shale, often contain naturally occurring radionuclides like uranium and radium, which can contribute to elevated indoor radon levels [20].

The degree of indoor pollution in such areas is influenced by several interacting factors, including proximity to the emission source, dominant

wind patterns, construction integrity, and the design and functionality of ventilation systems. To mitigate these exposures, strategies such as the installation of air filtration units, sealing of structural leaks, and the use of vegetation barriers have been proposed [21]. Despite these efforts, few studies have jointly assessed the indoor presence of both particulate matter and radon in residential environments affected by industrial emissions.

This study was undertaken to address the limited data on combined indoor exposure to particulate matter and radon in communities located near cement production facilities in Nigeria. Indoor concentrations of $PM_{2.5}$, PM_{10}, and radon were measured in residential buildings situated close to two major cement factories in Ogun State. Sampling was conducted during the August break, a short dry-season period characterized by relatively stable atmospheric conditions, thereby reducing meteorological variability and improving the reliability of the measurements. By focusing on indoor environments where residents spend most of their time, this study provides a realistic assessment of routine exposure in industrial host communities.

The specific objectives were threefold. First, to quantify indoor concentrations of $PM_{2.5}$, PM_{10}, and radon gas in homes located near cement manufacturing operations. Second, to evaluate the associated non-carcinogenic and carcinogenic health risks using established United States Environmental Protection Agency and International Commission on Radiological Protection risk assessment models. Third, investigate the correlation between indoor particulate matter and radon concentrations in order to assess the extent of combined pollutant exposure. Collectively, these analyses provide new evidence on indoor air contamination in cement-producing regions and offer a scientific basis for risk management strategies aimed at protecting exposed populations.

Materials and methods

Study area and sampling locations

The study was carried out in two industrially significant towns in Ogun State, Southwestern Nigeria: Ewekoro and Ibese. These towns are home to two of the largest cement manufacturing facilities in West Africa and have undergone rapid industrial expansion in recent years.

Ewekoro is situated at approximately 6°56′N latitude and 3°13′E longitude, covering an estimated land area of 594 square km. The town has a growing population of over 55,000 residents. The twenty (20) smapling points of the resisdent are shown in Fig. 1 on the map in reference to the cement depot. The climatic conditions in the study area are typical of a humid subtropical zone, featuring distinct dry and wet seasons. The dry season spans from December to March and is marked by high temperatures and low humidity, while the wet season extends from April through late September, bringing frequent rainfall and dense cloud cover. Average wind speeds are around 10 km/h, with prevailing winds blowing predominantly from the southwest. Relative humidity ranges from about 56 percent during drier periods to as high as 88 percent during peak rainfall. Ambient temperatures generally fluctuate between 24 o C and 34 o C throughout the year. Air quality assessments were carried out during the "August break," a brief seasonal period occurring between mid-July and late August, characterized by low rainfall, moderate winds, and cooler temperatures. These conditions provided a stable atmospheric window ideal for monitoring indoor and outdoor air quality. The metrological parameters and geological position of the study area showing GPS, the average temperature and relative humidity over the period the period of 30 days is showing in Table 1.

Table 1. Metrological parameters and geological position of the study area

Name	Longitude	Latitude	Temp.(°C)	R. Humidity(%RH)
E1	3.203334410	6.899722593	35.6	51
E2	3.203170469	6.899857258	35.0	50
E3	3.202895283	6.899980214	37.8	46
E4	3.202643518	6.900068039	35.6	48
E5	3.202309782	6.900208559	32.8	54
E6	3.202151696	6.899915809	33.3	54
E7	3.202210246	6.899488392	36.7	48
E8	3.202110711	6.899289322	35.6	50
E9	3.203041659	6.899271757	35.0	50
E10	3.201929205	6.899459117	32.8	52
E11	3.201630599	6.899459117	32.2	55
E12	3.201993611	6.899037556	30.6	59
E13	3.202321492	6.899049266	30.0	62
E14	3.201964336	6.898692110	29.4	64
E15	3.202221956	6.898838485	29.4	64
E16	3.202421027	6.898534024	30.0	63
E17	3.201888220	6.898422779	30.6	63
E18	3.202134131	6.898440344	31.1	65
E20	3.201695005	6.898662835	32.8	57

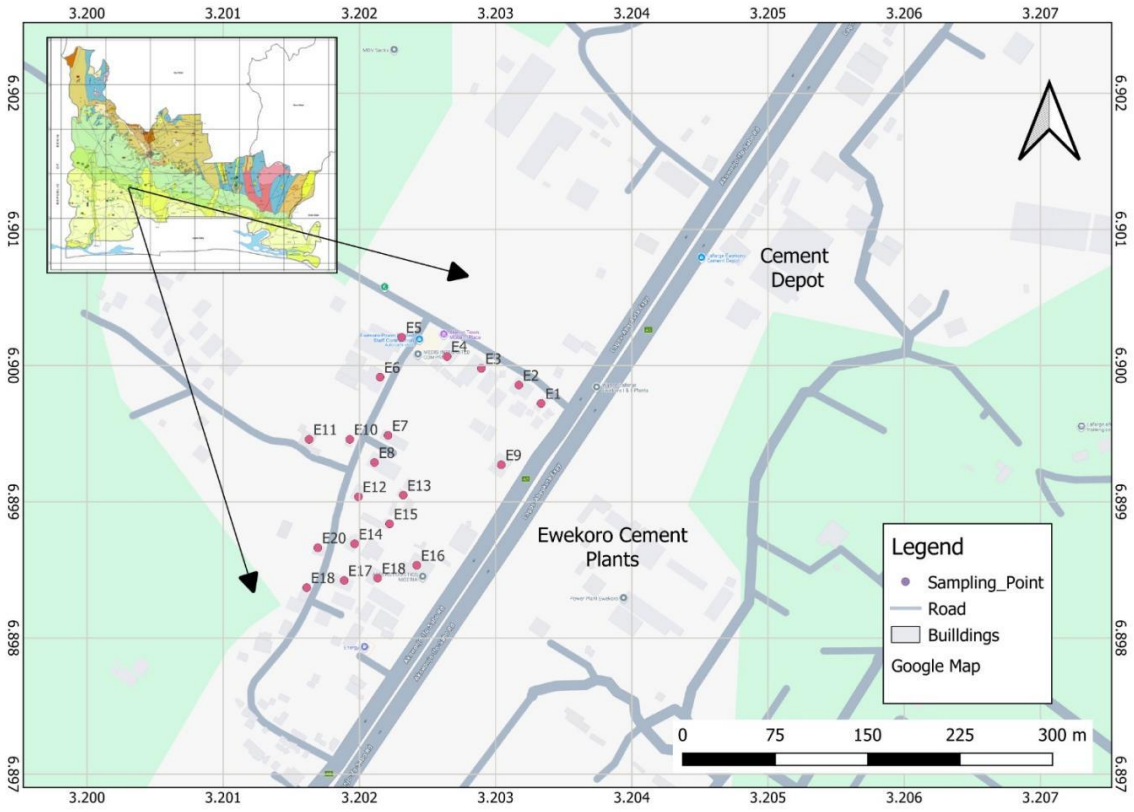

Fig. 1. The GPS location of the sampling points and cement factory

Instrumentation and measurement of air quality parameters

Particulate matter concentrations in indoor and outdoor environments were measured using the Elitech Temtop LKC-1000S Plus air quality monitor. This instrument provides real-time data on mass concentrations of $PM_{2.5}$ and PM_{10}. It also records temperature, relative humidity, and calculates the Air Quality Index. The device includes a histogram function that displays changes in PM concentrations over the past twelve hours.

Twenty residential buildings located within a two km radius of the cement factories were randomly selected for air quality monitoring. All selected buildings relied on natural ventilation, and measurements were taken on the ground floor. Indoor and outdoor concentrations of $PM_{2.5}$ and PM_{10} were measured twice daily, during early morning and late evening hours, for a total of thirty consecutive days within the August break period. Indoor measurements were recorded every six hours, with each session lasting approximately thirty minutes. The air quality monitor was placed at a height of 1.5 m above the floor, centrally located in each indoor space to reflect the typical breathing zone of occupants [22, 23]. Outdoor samples were collected at a distance of 2 m from the nearest window of each building. Although the primary focus of the study was indoor air

quality, outdoor measurements were included to assess the degree of correlation between indoor and outdoor pollutant sources.

Indoor radon measurement

Indoor radon concentrations were measured over a short term using CR-39 solid-state nuclear track detectors housed in passive diffusion chambers. A total of twenty CR-39 detectors were deployed in the same buildings used for particulate matter assessment. Each detector consisted of a 10 mm × 10 mm^2 polymer film with a thickness of 1 mm. The detectors were suspended between 1.5 and 2 m above the floor (within the occupants' breathing zone) and left in place for thirty days. After exposure, the detectors were retrieved and chemically etched in a 6 M sodium hydroxide solution. Etching was performed by immersing the detectors in this solution held in a water bath at a constant temperature of 80 °C for 3.5 h. Following etching, the detectors were examined under an optical microscope at 400× magnification, with images recorded on a connected computer. The alpha-particle tracks on the CR-39 films were counted using ImageJ software. Track densities were then converted into radon concentrations by applying a calibration factor derived from pre-exposed reference detectors. Finally, radon concentration values were calculated using a calibration equation (Eq. 1).

$$C_{Rn}=\frac{\rho-\rho_B}{Kt} \quad (1)$$

Where:

CRn is the radon concentration in $Bq\cdot m^{-3}$, ρ is the track density on the CR-39 detector; ρB is the background track density in detectors. K is the calibration factor of CR-39 detector in $(track/cm^2)/(Bqh/m^3)$ and t is the effective exposure time in hours. The relation in Eq. 2 gives the calculation of K [24]

$$K=\frac{\rho_o-\rho_{Bo}}{C_0 t} \quad (2)$$

Where:

Co is the integrated concentration in Bq/m^3 in the standard radon chamber. ρo is the irradiated track density in $track/cm^2$, ρBo is the background track density in $track/cm^2$ and t is the exposure time.

Health risk assessment model for particulate matter

This study used US EPA model for the estimation of the human health risk due to inhalation of particulate matter. Eq. 3 was used for the calculation of average daily intake (ADI) (mg/kg.day) for $PM_{2.5}$ and PM_{10} contaminants [25, 26].

$$ADI=\frac{C_{pm}\times I_R \times E_F \times T_E \times \mathrm{D_E}}{B_W \times \mathrm{T_m}} \quad (3)$$

Where: The parameters and values required for computing non-cancerous risk for adult (>18 years) are:

C_{pm} is the concentration of the PM ($\mu g/m^3$)

I_R is the inhalation rate (m^3/day)= IR = 20 m^3/day,

T_E is the exposure time (h/day) = 12 hours/day,

E_F is the exposure frequency (day/year)=365 day/year,

D_E is the duration of exposure (years)= 30 years,

B_W is the body weight (kg) = 70kg,

M_T is the mean time (days) = ED (years) × 365 days/year.

The characterization of non-carcinogenic

health risk factor risk due to $PM_{2.5}$ and PM_{10} was calculated by using the dose reference (RfD) (mg/kg.day) with the Reference Concentrations (RfC) for $PM_{2.5}$ and PM_{10} as 5 µg/m^3 and 50 µg/m^3 respectively. The Hazard Quotient (HQ) gives the indicator of the magnitude of the no-cancer risk. Using USEPA criterion to estimate total hazard quotient that gives the inhalation of many pollutants at the same time is the hazard index (HI) as seen in Eqs. 4 and 5. HI < 1 reflects, no significant (acceptable) risk and HI > 1 suggests that the non-carcinogenic effect is probable to appear, whereas a high chronic risk is denoted for HI > 10 [27].

$$HQ = \frac{ADD}{RfD} \quad (4)$$

$$HI = \Sigma(HQ_{PM2.5}) + \Sigma(HQ_{PM10}) \quad (5)$$

Radon exposure dose and cancer risk assessment

Radon exposure is a health concern because the gas can accumulate in buildings, especially in spaces with elevated radioactive background level and high influx from external source due to variation in diffusion gradient [28]. Persistent exposure due to high radon levels can surge the risk of lung cancer. To assess radon exposure, measurements are often expressed in terms of Working Levels (WL) or Equilibrium Equivalent Radon Concentration (EEC). One working level is defined as the amount of radon decay products that release 1.3 × 10^5 MeV of Potential Alpha Energy (PAE) per liter of air. It provides a measure of the rate of decay product concentration in the air. EEC on the other can be derived from Equation 5 and converted into Potential Alpha Energy concentration (PAE) using Eqs. 5 and 6 [29].

Where, 1 WL is the concentration of PAE related with the radon progeny in equilibrium with 3700 Bq/ m^3)

$$EEC = C_{Rn} \times E_r \quad (6)$$

$$\mathrm{WL} = \frac{C_{Rn} \times E_r}{3700} \quad (7)$$

In this study UNSCEAR model EEC was used for the calculation of annual absorbed dose, and the annual effective dose rate from exposure to inhaled radon (222Rn) and its progeny to the public were Computed by the Eqs. 7 and 8 [30].

$$AED_{Rn} = EEC \times O_t \times t \times D_{Cf} \quad (8)$$

Where: ADERn is the annual absorbed dose in mSvy^{-1} from exposure to radon in air, Ot is the Occupancy time is 0.8 of time, T = 24 h ×365 = 8760 h/year spent in an indoor space, DCf is the Dose conversion factor (9×10^{-6} mSv/Bqhm^{-3}). CRn is the mean Radon concentration in Bqm $^{-3}$ and Er = the indoor radon equilibrium ration = 0.4.

$$H_{Rn} = AED_{Rn} \times W_R \times W_T \quad (9)$$

Where: HRn is the annual effective dose rate for inhaled ^{222}Rn and progeny, WR = 20 is the radiation-weighting factors (for alpha particle emitter) and WT = 0.12 is the lung tissue-weighting factor [31, 32].

The excess lifetime risks (ECLR) is a scholastic prediction of the potential of an individual or group of people to experience carcinogenic effects in the lungs due to inhaled ^{222}Rn and its progeny. The ECLR using ICRP model for an exposure period, T, of 30 years for the general population with a risk factor L R = 0.055 Sy^{-1}

is given in the Eq. 9 [33].

$$ELCR=AED_{Rn} \times L_R \times T \quad (10)$$

Results and dissuasion

Indoor and outdoor concentrations of particulate matter

Table 2 presents the integrated concentrations of fine ($PM_{2.5}$) and coarse (PM_{10}) particulate matter measured over a 30-day period in both indoor and outdoor environments within the study area. The mean indoor concentration of $PM_{2.5}$ was 39.94 µg/m³, with individual measurements ranging from 33.8 to 49.6 µg/m³. For PM_{10}, the average indoor concentration was 60.83 µg/m³, with a range of 50.2 to 74.8 µg/m³. Corresponding outdoor concentrations were notably higher, with $PM_{2.5}$ and PM_{10} averaging 64.56 µg/m³ and 101.95 µg/m³, respectively.

All measured indoor concentrations of $PM_{2.5}$ and PM_{10} exceeded the World Health Organization (WHO) recommended guideline values. According to the latest WHO guidelines, the annual average indoor concentrations for $PM_{2.5}$ and PM_{10} should not exceed 5 µg/m³ and 15 µg/m³, respectively, while the daily exposure limits are set at 15 µg/m³ and 45 µg/m³ [34, 35].

The indoor-to-outdoor (I/O) concentration ratios for $PM_{2.5}$ and PM_{10} were calculated to be 0.652 and 0.642, respectively. These ratios suggest that a substantial portion of indoor particulate matter originates from outdoor sources. The minimum and maximum I/O ratios for $PM_{2.5}$ were 0.288 and 0.945, while those for PM_{10} ranged from 0.31 to 1.116. Most I/O ratios for both PM fractions were less than one, indicating that indoor concentrations were generally lower than those outdoors. Only one instance of PM_{10} showed an I/O ratio slightly exceeding unity, which may reflect localized indoor sources or poor ventilation.

The predominance of outdoor particulate matter in indoor air is consistent with the natural ventilation systems used in the sampled buildings. Proximity to cement factories, which emit particulate matter through raw material handling, kiln combustion, and heavy vehicular traffic, likely contributes to elevated outdoor PM concentrations [36]. These emissions can easily infiltrate indoor environments through windows, doors, and other openings, particularly in buildings lacking adequate sealing or insulation [18].

Beyond emissions from industrial sources, everyday human activities like gardening, sweeping, and outdoor play can also contribute to the movement of particulate matter into indoor environments. To reduce exposure, practical measures such as the use of air filtration systems and the planting of vegetation barriers, including trees and shrubs, have been suggested. These interventions can help lower indoor levels of particulate matter and support better respiratory health, particularly for residents living close to industrial facilities [37].

Table 2. Concentrations of the indoor and outdoor $PM_{2.5}$ and PM_{10}, and indoor concentration of radon

S.n	Indoor			Outdoor						
	$CPM_{2.5}$ (μgm^{-3})	CPM10 (μgm^{-3})	C_{Rn} (Bqm^{-3})	$CPM_{2.5}$ (μgm^{-3})	CPM10 (μgm^{-3})	$CPM_{2.5}$ [I/O]	CPM10 [I/O]	HQ2.5	HQ10	HI
E1	33.8±12.5	50.2±12.5	89.0±2.5	62±2.4	16.02±7.5	0.545	0.309	2.3	1	3.3
E2	34.0±20.1	51.2±18.6	65.0±3.8	118±1.2	162.0±2.9	0.288	0.316	2.3	1	3.3
E3	39.0±2.6	58.7±21.9	102.0±9.5	84.0±1.3	116.0±8.9	0.464	0.506	2.6	1.2	3.8
E4	40.0±4.9	60.5±19.5	95.0±2.9	75.4±1.6	119.4±1.9	0.531	0.507	2.7	1.2	3.9
E5	35.0±17.8	52.1±8.9	69.0±5.8	47.6±2.9	74.9±2.9	0.735	0.696	2.3	1	3.3
E6	36.2±7.2	55.5±14.8	98.0±7.6	59.9±2.6	93±2.9	0.604	0.597	2.4	1.1	3.5
E7	38.7±18.6	57.0±15.8	103.0±2.8	56.8±5.9	88.4±9.2	0.681	0.645	2.8	1.1	3.9
E8	35.8±8.4	53.0±10.8	109.0±8.5	50.9±8.9	82.1±7.9	0.703	0.646	2.4	1.1	3.5
E9	35.6±4.5	52.3±13.9	102.0±5.8	61.9±9.6	101.9±2.5	0.575	0.514	2.4	1.1	3.5
E10	35.2±2.5	52.1±12.5	105±12.8	65.7±7.9	109.0±12.9	0.536	0.478	2.4	1	3.4
E11	42.4±12.8	64.7±10.9	99.5±10.5	58.8±8.9	97.0±7.6	0.721	0.668	2.8	1.3	4.1
E12	43.0±3.5	65.8±15.9	82.5±12.4	48.3±2.9	75.0±5.7	0.89	0.877	2.9	1.3	4.2
E13	44.8±9.2	68.8±7.5	99.4±3.9	80.3±1.8	120.3±5.9	0.558	0.572	3	1.4	4.4
E14	40.8±14.8	63.5±2.9	120.5±5.7	52.7±2.9	81.3±2.9	0.774	0.781	2.7	1.3	4
E15	41.6±9.5	65.4±5.9	50.6±6.5	55.0±5.8	58.6±7.9	0.756	1.116	2.8	1.3	4.1
E16	42.0±10.2	65.9±11.6	111.2±2.8	83.4±8.4	141±7.2	0.504	0.467	2.8	1.3	4.1
E17	38.4±16.8	61.1±13.5	103.5±5.9	53.9±2.9	87.6±54.9	0.712	0.697	2.6	1.2	3.8
E18	45.7±15.8	71.5±20.8	88.7±8.9	66.7±8.9	101.5±9.5	0.685	0.704	3	1.4	4.4
E19	47.1±2.8	72.5±18.6	87.2±4.9	57.3±4.9	79.0±11.5	0.822	0.918	3	1.5	4.5
E20	49.6±7.6	74.8±12.8	69.5±5.4	52.5±7.9	89.0±4.8	0.945	0.841	3.3	1.5	4.8
Mean	39.94	60.83	92.48	64.56	101.95	0.652	0.6427			
Min	33.8	50.2	50.6	47.6	58.6	0.2881	0.3099			
Max	49.6	74.8	120.5	118.0	162.0	0.9448	1.1160			

$CPM_{2.5}$: Concentrations of $PM_{2.5}$, CPM_{10}: Concentrations of PM_{10}, C_{Rn} : Concentrations of radon

Hazard quotients and hazard index of particulate matter

The assessment of non-carcinogenic health risks related to indoor air pollution in the study area involved calculating Hazard Quotients (HQ) for adult inhalation exposure to $PM_{2.5}$ and PM_{10}. The Reference Concentrations (RfC) applied in the hazard quotient calculations were 5 µg/m³ for $PM_{2.5}$ and 50 µg/m³ for PM_{10}, derived from US EPA inhalation toxicology guidance. The average daily intake (ADI) was computed using the following exposure parameters: an Inhalation Rate (IR) of 20 m³/day, an Exposure Frequency (EF) of 365 days/year, an Exposure Duration (ED) of 30 years, and a Body Weight (BW) of 70 kg. These parameters are consistent with US EPA default assumptions for chronic adult inhalation exposure and reflect a continuous, long-term exposure scenario representative of residents in proximity to a stationary emission source.

Cumulative risk was quantified using the Hazard Index (HI), which sums the HQs of individual pollutants. The HQ values for $PM_{2.5}$ ranged from 2.3 to 3.0, while those for PM_{10} ranged between 1.0 and 1.5. All values exceeded the acceptable risk threshold of 1.0, indicating exposure levels that may lead to adverse health outcomes.

The overall HI values ranged from 3.3 to 4.8, with a mean of 3.89, reflecting a significant probability of chronic non-cancer health effects from prolonged inhalation. According to the United States Environmental Protection Agency (US EPA), an HI above 1 signifies potential health concern arising from cumulative pollutant exposure [25].

These findings are consistent with previous studies conducted in industrial and residential settings impacted by cement production and particulate emissions [39-44]. For example, high HQ values have been recorded near limestone quarries even at distances greater than 2 km from the source [39]. Although this study focused on indoor environments, the results point to wider public health implications for those living or working near industrial facilities.

In the absence of effective control measures—such as the use of personal protective equipment or limiting exposure duration—these populations remain vulnerable. Supporting evidence from occupational settings in cement processing and packaging has similarly shown HQ values consistently above unity, reinforcing the need for targeted health risk mitigation [45].

Indoor radon concentrations and exposure dose

This study also investigated indoor radon concentrations and estimated the associated annual effective dose and Excess Lifetime Cancer Risk (ELCR) for residents in buildings situated near a cement production facility. The mean indoor radon concentration across the sampled homes was 92.48 ± 17.12 Bq/m³, with measured values ranging from 50 to 120.65 Bq/m³. Notably, 40% of the sampled buildings recorded radon concentrations above the World Health Organization's (WHO) reference level of 100 Bq/m³.

The annual effective dose due to radon inhalation ranged from 0.081 to 2.20 mSv/year, with a mean value of 1.41 ± 0.514 mSv/year. Correspondingly, ELCR values spanned 3.56 to 20.33 per million persons, with a mean risk of 13.42 per million. Although these ELCR values fall within the US EPA's acceptable carcinogenic risk range (≤100 per million), they represent a non-trivial and noteworthy

risk level, particularly given the likelihood of sustained long-term exposure among residents in this industrial zone. The mean ELCR of 13.42 per million, while below the regulatory ceiling, nonetheless warrants attention from a public health perspective, especially for vulnerable sub-populations.

Radon concentrations in indoor environments are influenced by multiple factors, including soil characteristics, building materials, ventilation rates, and construction practices. The elevated levels recorded in several of the study homes suggest that radon entry is likely facilitated by underlying geological features and insufficient structural barriers. The highest dose values recorded exceeded 2 mSv/year and are well above the WHO's recommended reference level of 1.3 mSv/year, indicating the need for remedial interventions. These results are consistent with global data from radon studies in various residential settings. For example, mean annual effective doses reported in Spanish and Chinese residences were approximately 1.15 and 1.37 mSv/year, respectively [45- 47], while those in Greece and the United Kingdom tended to be lower, averaging between 0.27 and 0.5 mSv/year [46-48]. Comparable ELCR values have also been reported in studies conducted in Italy, Poland, and Saudi Arabia, with mean risks ranging from 10 to 14.5 per million persons [49– 51].

Given the proportion of dwellings exceeding international safety limits, the findings of this study underscore the need for targeted radon mitigation strategies. These may include improved natural or mechanical ventilation, sealing of entry points in building foundations, and installation of radon sump systems. In addition, public health interventions such as awareness campaigns and subsidized radon testing programs could play a crucial role in reducing long-term exposure and associated health risks.

Correlation between indoor PMs and radon

This study explored the relationships between indoor levels of particulate matter ($PM_{2.5}$ and PM_{10}) and radon gas (CRn) in homes located near a cement and limestone factory. The co-variation of $PM_{2.5}$ and PM_{10} ($r = 0.9877$) is consistent with the hypothesis that both fractions share overlapping emission sources, including raw material handling, kiln dust, and vehicular traffic associated with the cement facility. However, this observation cannot be interpreted as proof of a causal relationship or used alone to confirm source co-attribution. Establishing shared origin would require dedicated source apportionment techniques such as receptor modelling or chemical mass balance analysis, which are beyond the scope of the present study. Notwithstanding this limitation, the strong co-variation indicates that when $PM_{2.5}$ concentrations were elevated at a given sampling location, PM_{10} concentrations were proportionally elevated as well. This pattern is consistent with aerodynamic particle behaviour across the fine and coarse size fractions under common turbulent dispersion conditions.

This strong association suggests that both pollutants may possibly share common emission sources, such as dust from raw materials, factory machinery, and truck traffic, although correlation alone does not establish causation.

However, the relationship between $PM_{2.5}$ and radon was very weak ($r = 0.0308$), as was the correlation between PM_{10} and radon ($r = 0.0117$). This suggests that particulate matter and radon levels in indoor air behave almost

independently. While particulate matter tends to come from industrial activities and outdoor infiltration, radon is more influenced by the geology of the area and the way buildings are constructed and ventilated. These results imply that efforts to reduce indoor air pollution in such environments should consider separate strategies. Air filters and emission control systems can help reduce particulate matter, while radon requires approaches such as improving building ventilation or sealing cracks in floors and walls. This observation is consistent with previous research that identified industrial emissions as major contributors to indoor PM levels [52, 53], while radon is typically driven by geological and structural factors [47, 54]. Studies have also shown that combining control technologies, including HEPA filtration for PM and radon mitigation systems, can significantly enhance indoor air quality [55, 56].

Conclusion

This study showed the considerable health risks associated with indoor air pollution in residential buildings located near cement manufacturing facilities in Ogun State, Nigeria. Measured concentrations of $PM_{2.5}$, PM_{10}, and radon were found to exceed the limits recommended by the World Health Organization, indicating both non-carcinogenic and carcinogenic health concerns for exposed populations. A fairly positive correlation between particulate matter and radon levels suggests a linked effect that further degrades indoor air quality and amplifies potential health risks. These findings emphasize the urgent need for robust air quality management in industrial zones. Implementing targeted mitigation strategies such as improved ventilation, pollution control technologies, and urban planning interventions can help reduce exposure. In addition, strong regulatory enforcement and public education initiatives are essential to raise community awareness and protect the health of residents living in close proximity to industrial sources.

Financial supports

There is no financial supports received for this study.

Competing interests

There is no conflicts of interest in the research and publication procedures.

Acknowledgements

The authors are grateful to the director of Central laboratory, Bells University of Technology, Ota, Nigeria, for providing the facilities used during the bench work of CR-39 analysis.

Ethical considerations

This study did not involve human or animal subjects, and no harm to human or animal life was anticipated. Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc) have been completely observed by the authors.

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