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Environmental Soil and Indoor Radon Measurement and Assessment of its Radiological Risk in Boundiali, Côte d'Ivoire

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Abstract Environmental radon can be a public health concern. This is why it is crucial to know its level and to implement its monitoring. In this survey, integrated radon measurements were performed using Solid State Nuclear Track Detector's (SSNTD) technique particularly with the LR 115 passive detector throughout the city of Boundiali. The annual soil radon concentrations obtained range from [(7± 3) to (45 ± 22)] kBq/m^3 with an average of (21 ± 9) kBq/m^3. In dwellings, the measured annual concentrations of this gas range from [(109 ± 49) to (741 ± 333)] Bq/m^3 with an average of (328 ± 149) Bq/m^3. The corresponding annual alpha effective doses received by the public range from [(3 ± 1) to (19 ± 9)] mSv with an average of (8 ± 4) mSv. Several concentrations and doses exceed the acceptable limits recommended by the World Health Organization (WHO) and the International Commission on radiological Protection (ICRP). Since radon is known as a human lung carcinogen, annual Excess Lung Cancer Risk (ELCR) per million persons for the population of this city was estimated. The average values are found between 197-623 and 262-722 using the United States Environmental Protection Agency (EPA) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) models respectively. The results obtained will help raise awareness among the population and advise them. These results will contribute to creating the national radon map. And they will also assist public authorities in developing a policy to mitigate radon risk in Côte d'Ivoire.

Keywords: *LR 115 detector, Radon concentration, Alpha effective dose, ELCR, Boundiali*

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1. Introduction

Radon-222 is a human lung carcinogen gas [1]. It is a part of the decay series of the radionuclide uranium-238 present everywhere in the earth's crust [2]. Radon travels from deep within the earth's crust to homes. It then accumulates inside houses because of the confined atmosphere, and can reach an injurious rate to our health [3].

According to the World Health Organization (WHO), the International Commission of Radiological Protection (ICRP), the International Atomic Energy Agency (IAEA) and other international organizations, it is crucial for countries to perform radon measurements for the prevention and mitigation of the risk [4]. In Côte d'Ivoire, some data are being collected in order to realize a national radon mapping. The present study constitutes a modest contribution to this project in the continuity of the previous works [5,6].

Generally, there are several factors that influence the indoor radon levels such as the site-specific geology [7]. The high uranium concentration in a site suggests a high probability of high indoor radon levels in houses at this site, and granitic soils commonly contain high concentrations of uranium, with subsequent high exhalation of radon gas [8,9]. Because the geology of the north of Côte d'Ivoire is dominated by granite [10], this study aims to investigate radon concentrations both in the soils and houses of Boundiali, a city in this area where radon gas measurement has never been undertaken before.

2. Materials and Method

2.1. General Information about the Selected Measurement Locations

This study was conducted in the city of Boundiali, the capital of the department with the same name, which is located in the northwest of Côte d'Ivoire at 9°32 north latitude and 6°29 west longitude. This city has approximately 93, 000 inhabitants in an area of 8.51 km^2 [11].

The different measurement sites were located using a GPS device (GARMIN), which made it possible to define their geographical coordinates grouped in Table 1. Figure 1 [12] and Figure 2 [13] show respectively maps of the city and the region of Boundiali with the different measurement sites and the geological formations consisting mainly of granites and granodiorites. But, the 26 sites were selected throughout the city by performing a regular grid sampling that provided reasonable spatial coverage.

2.2. Measurement Activities and Devices Description

The device used for radon measurement in the dwellings consisted of a plate on which the SSNTD LR 115 detector (commercially available, LR-115 type 2 non-strippable films manufactured by DOSIRAD, France) was attached (Figure 3). With the help of a double-sided adhesive, the plate was glued at best, on the side of a cabinet or failing that on the wall, at a height of between 1 and 2 m from the floor, slightly away from the doors and windows. The date and time of installation were recorded. Some architectural features of the house (ventilation, house floor level, and cracks in the walls) were also recorded. At the same time, the radon activity in the air of bare soil near the investigated houses was measured because the measurement of the radon emanation from the soil just below these houses could not be carried out due to a lack of adequate tools. The average distance between the soil sampling points and the corresponding dwellings was 10 m. Radon measurements in the soil were performed using a hollow PVC tube with a length of 30 cm and a diameter of 4 cm, provided with a wooden cap on which the SSNTD was fixed (Figure 4). The choice of 30 cm length for the tube allows the potential residual thoron effect as a limitation [14]. The device was placed in a hole 80 cm deep and 15 cm in diameter, so that the open end of the tube was placed at the bottom of the hole. The latter was then closed with a plastic film on which a wooden plank was placed and the entire plank was covered with sand. We also recorded the date and time of installation. Plastics and wood have been used as thermal insulators. Their presence was necessary in order to overcome the problems of moisture and condensation that could occur deep in the soil. Indeed, if the detector temperature falls below the dew point (condensation temperature of water vapor), water droplets form on its sensitive face. Because, the range of radon alpha particles in water is extremely short, the formation of these droplets would distort the measurements if it occurs [15,16].

Soil samples were taken from different horizons (layers of earth in the hole that can be distinguished, for example, by their color) in each hole to determine the porosity and particle size compositions of the soil.

All SSNTD were exposed at the different sites, in houses and soils, during each of the wet and dry seasons, for a period of time of two months at least (Table 1).

Table 1. Information regarding measurement sites

Measurement site	GPS Localisation	Detector exposure time (h)
B1	N 9°30.879 W 6°28.325	1675
B2	N 9°31.632 W 6°28.673	1694
B3	N 9°31.479 W 6°28.528	1667
B4	N 9°31.309 W 6°29.536	1556
B5	N 9°31.720 W 6°28.085	1666
B6	N 9°31.442 W 6°27.994	1657
B7	N 9°31.278 W 6°28.290	1782
B8	N 9°31.796 W 6°29.035	1679
B9	N 9°31.663 W 6°28.945	1685
B10	N 9°31.045 W 6°29.385	1560
B11	N 9°31.811 W 6°28.272	1657
B12	N 9°31.381 W 6°29.003	1681
B13	N 9°31.548 W 6°28.232	1678
B14	N 9° 31.994 W 6°29.012	1695
B15	N 9°30.944 W 6°28.689	1658
B16	N 9°31.907 W 6°27.807	1680
B17	N 9°31.816 W 6°28.472	1681
B18	N 9°31.889 W 6°28.795	1668
B19	N 9°32.311 W 6°28.826	1561
B20	N 9°30.676 W 6°28.974	1666
B21	N 9°30.852 W 6°29.128	1669
B22	N 9°31.201 W 6°29.079	1667
B23	N 9°31.230 W 6°29.312	1657
B24	N 9°30.426 W 6°28.771	1758
B25	N 9°31.148 W 6°28.869	1671
B26	N 9°31.557 W 6°27.992	1557

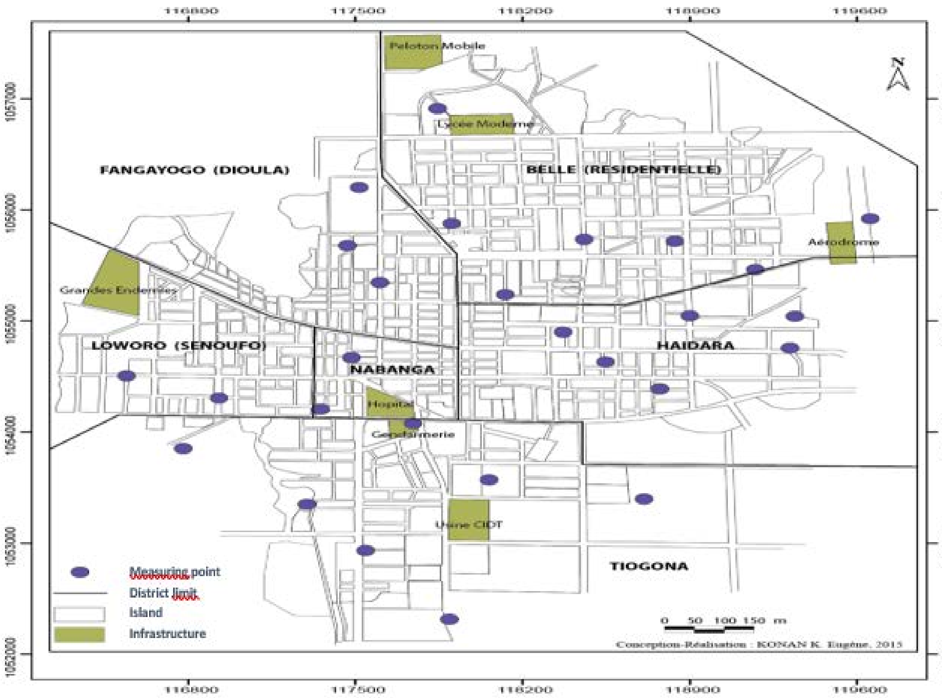

Figure 1. Map of Boundiali showing the measurement points

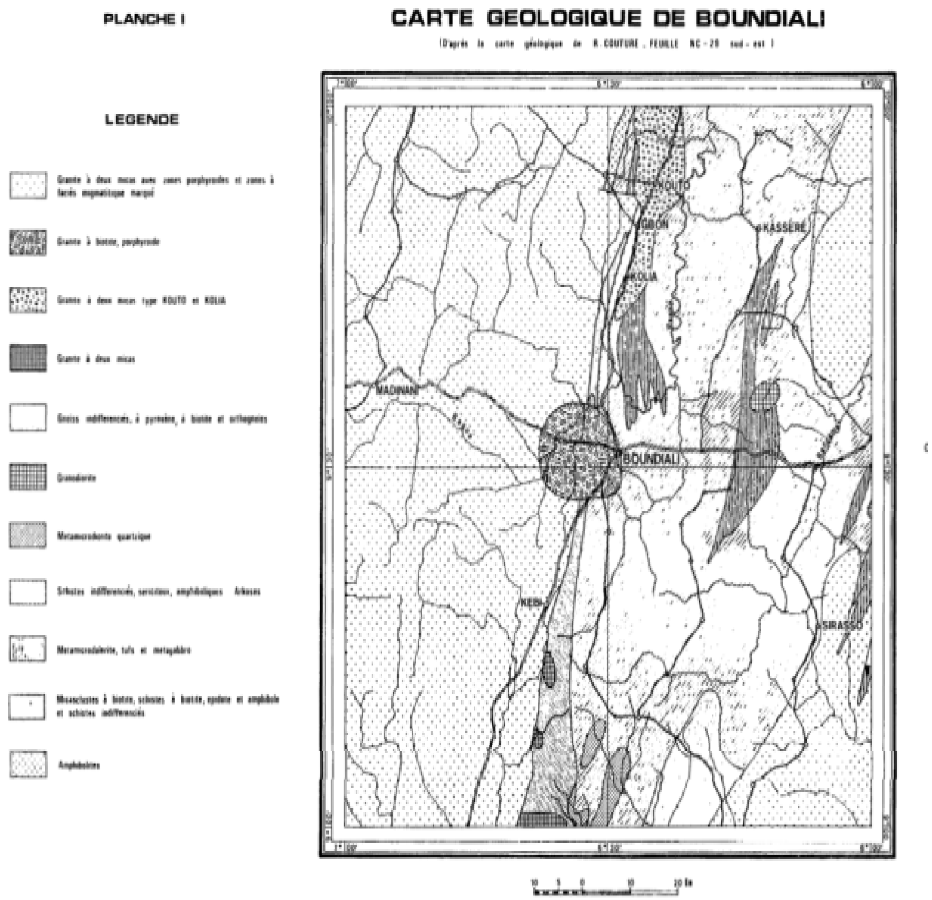

Figure 2. Geological map of Boundiali

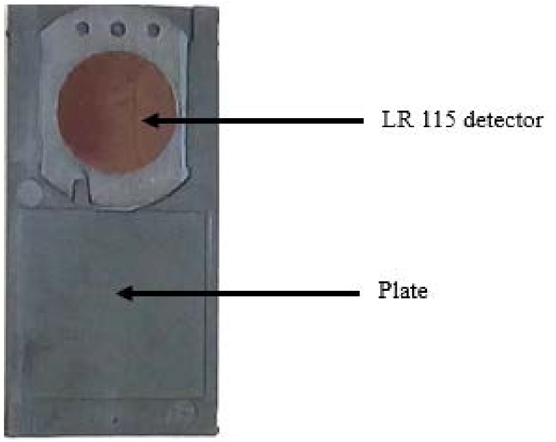

Figure 3. Photo of indoor radon measuring device

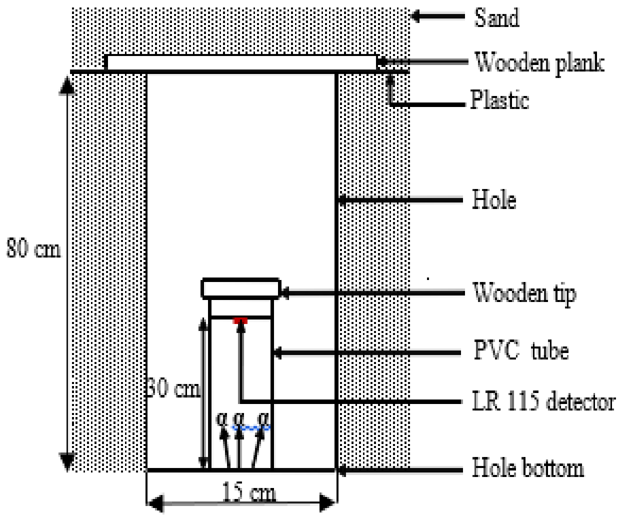

Figure 4. Diagram of soil radon measuring device in a hole

2.3. Analysis of Detectors and Soil Samples

All SSNTD pieces exposed to radon were chemically etched for 120 min, under standard conditions, that are, in a NaOH solution of concentration 2.5 mol/L, set to temperature maintained at 60°C [17,18]. The alpha particle tracks revealed on their surfaces were then counted using an optical microscope.

Soil samples were analyzed to determine the total porosity and particle size compositions at the Waters-Soils-Plants Laboratory of the Agronomy Engineering School in Yamoussoukro's (Côte d'Ivoire) Houphouët Boigny National Polytechnic Institut (INPHB).

2.4. Detector Calibration

The CRNA radon chamber was used to determine the SSNTD-LR 115 radon calibration factor (k). Sheets of LR 115 were placed in the exposure chamber with a parallel AlphaGuard (AG) PQ2000 PRO radon detector (Saphymo®, Germany) which was used as a reference device. The AG device was used with a standard NIST-certified Rn-222 source of concentration (1.99 ± 0.93) kBq/m^3 in a 101.1-liter cylindrical stainless steel calibration chamber. The standard NIST-certified source (SRM 4973) contained Ra-226 with an activity of 449 ± 6 Bq and a Rn-222 gas emanation fraction of 0.88 ± 0.01 at 21°C. An electronic pump was also used to transfer the accumulated Rn-222 gas without loss or dilution. The ^{222}Rn concentrations (C_{Rn}) obtained in the calibration chamber were measured using the AG radon monitor. The average ^{222}Rn concentration in the chamber was equal to 1.99 kBq/m^3 for 64.33 hours.

2.5. Methods of Calculation

2.5.1. Radon Concentration Calculation

Radon concentration was calculated by the formula:

$$C_{Rn} = \frac{\rho - \rho_0}{k.t} \quad (1)$$

Where
C_{Rn} is radon concentration (kBqm^{-3});
k the calibration factor (tracks cm^{-2}/kBqm^{-3}h);
t the exposure time (h);
ρ the track density (tracks cm^{-2});
and ρ_0 the background (tracks cm^{-2}).

The measured calibration factor values were (198 ± 89) tracks cm^{-2}/kBqm^{-3}h and (173 ± 78) tracks cm^{-2}/kBqm^{-3}h for the soil and indoor radon detectors respectively.

For each detector batch, the relative uncertainty in the radon concentration was calculated using the following formula derived from (1):

$$\left(\frac{\Delta C_{Rn}}{C_{Rn}}\right)^2 = \left(\frac{\Delta\rho}{\rho}\right)^2 + \left(\frac{\Delta k}{k}\right)^2 \quad (2)$$

where
ΔC_{Rn} is the uncertainty in the radon concentration;
Δρ the statistical uncertainty in the track density;
and Δk the uncertainty in the calibration factor.

2.5.2. Radon Effective Dose Evaluation

For evaluating doses from radon exposure levels to a population, and considering the last report of UNSCEAR which states that regarding the uncertainties of risk estimation from both dosimetric and epidemiological studies, the UNSCEAR recommends keeping the value of the dose conversion factor of 9 nSv per (h Bq m^{-3}) EEC of ^{222}Rn, which corresponds to 1.6 mSv per mJhm^{-3} [19].

2.5.3. Estimation of the Excess Lung Cancer Risk (ELCR) from radon

The Excess Lung Cancer Risk (ELCR) is defined as the number of deaths per million people per year (MPY) due to lung cancer as a result of exposure to radon and its daughter products. It was determined from the epidemiological data of occupationally exposed mine workers. Although, limited data are available on lung cancer cases due to indoor radon exposure, the risks appear to be consistent with earlier estimates based on data from mine workers. Hence, to assess the lung cancer prevalence in the general population, the risk of indoor radon exposure is usually considered for mine workers. Numerous models for estimating the risk of lung cancer resulting from indoor radon exposure have been reported in the literature [20,21]. The ELCR related to radon was evaluated using graphs from UNSCEAR (United Nations

Scientific Committee on the Effects of Atomic Radiations) and US-EPA (Environmental Protection Agency-USA) data as shown in Figure 5 [22]. There is a wide variation in the estimated values of excess lung cancer risk. The lower and higher limits of ELCR coefficients used for calculation were (0.6-1.9) MPY and (0.8-2.2) MPY per Bq/m^3 for EPA and UNSCEAR models respectively.

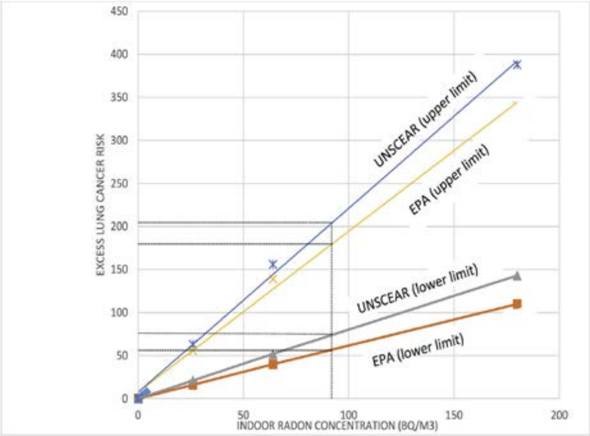

Figure 5. ELCR as a function of indoor radon concentration

3. Results and Discussion

Table 2 and Table 3 contain our main results. These are radon concentrations, factors affecting these concentrations, and risk assessment. The relatively high uncertainties of radon concentrations (40 - 48 %) are due to the radon source used during calibration process. The exposure time of the detectors was weighted equally and seasonal trends in the levels of concentrations were not observed. So, we calculated the arithmetic mean of the seasonal concentrations to obtain the annual concentration.

3.1. Soil radon Concentration

The highest values of radon concentrations in soils were measured at sites B24 and B25 (40 – 45 kBq/m^3), and the lowest at sites B19 and B26 (7 kBq/m^3). Only 15 % of locations had a concentration below 10 kBq/m^3 which is the maximum limit value of radon concentration corresponding to a negligible risk. The 85 % have a concentration exceeding this limit set by the Swedish criteria, suggested by Akerblom, and used for soil radon risk classification [23]. Indeed, the Sweden has a good radon mitigation policy. They succeeded, with appropriate protective measures, in significantly reducing the average concentration of radon in their houses after studies showed that this gas comes mainly from their soil [24]. The average annual radon concentration in the soil of the city of Boundiali is 21 kBq/m^3. Thus, radon risk in the soil of this city is moderate and therefore not negligible. This result could explain the granitic nature of this soil.

At sites B4 and B11, soil porosities are almost the same (38.74% and 36.42%), but clay and fine silt particle size compositions are higher at site B4 (128.60 g/kg and 112.20 g/kg) than at site B11 (58.60 g/kg and 67.08 g/kg). We also notice that soil radon concentration is higher at B4 (26 kBq/m^3) than at B11 (14 kBq/m^3). These results could demonstrate the influence of particle size distribution on soil radon emanation, indeed, the smaller the grains, the greater the radon emanation [25,26].

3.2. Indoor Radon and Influencing Factors

In dwellings, according to the values listed in Table 2, annual concentrations vary from 109 Bq/m^3 at site B9 to 741 Bq/m^3 at site B13 with an average of 328 Bq/m^3, which is higher than that of the granitic department of Cantal in France whose average value is 161 Bq/m^3 [27]. The histogram of concentrations (Figure 6) shows that 32% (This could be slightly higher or lower if we had the data from site B12) of the obtained results exceeded the upper level of 300 Bq/m^3 recommended by ICRP and WHO for immediate actions and 68% below this level [28].

At site B25, we have the greatest soil radon concentration (45 kBq/m^3), but indoor radon concentration is one of the smallest there (243 Bq/m^3). This could be due to the high floor level of the house and the low porosity of the soil (34%).

At site B5, the soil radon concentration is one of the smallest (16 kBq/m$^{3)}$), but the indoor radon concentration is one of the greatest (714 Bq/m^3). May be because ventilation inside the house is medium, there are cracks in the wall and the floor level of the house is low.

The correlation between the soil and indoor radon concentrations is fairly good for only 20% of the measurement sites and poor for the rest. This result might be due to the soil radon that was not measured in the soil directly beneath the houses.

Based on the results in Table 2 and Table 3 and those from literature review, the elevated indoor radon concentrations could be due to soil radon concentrations, cracks in the walls, poor indoor ventilation, low level of floor in contact with the the ground, and soil porosity [29].

3.3. Effective dose and ELCR

The corresponding annual effective doses received by the public varied from 3 to 19 mSv with an average of 8 mSv. 28 % (This could be slightly different if we had the data of B12) of the values obtained exceeded the ICRP annual limit of 10 mSv [30].

Excess lung cancer risks (ELCR) have been estimated for a lifetime age of 70 years using the risk coefficients recommended by the UNSCEAR and EPA. The ELCR values per MPY were considerable. Among 1 million people, 65 to 1408 with an average of 197-623 and 87 to 1630 with an average of 262-722 could be victims of death due to lung cancer from radon exposure each year at Boundiali according to the EPA and UNSCEAR models respectively. It is evident from these results that the excess lung cancer risks calculated using the risk coefficients recommended by the EPA and UNSCEAR respectively differs from one another for identical indoor radon activity concentrations. As previously mentioned, this variation can be due to diverse assumed parameters.

Table 2. Qualitative and quantitative values of factors influencing soil and indoor radon concentrations in Boundialy

Site	House ventilation	House wall crack	House floor level	Soil porosity (%)	Soil's clay (g/kg)	Soil's fine silt (g/kg)	Soil's coarse silt (g/kg)	Soil's fine sand (g/kg)	Soil's coarse sand (g/kg)
B1	Medium	No	High	55	111,71	120.66	132.38	292.59	342.65
B2	Medium	Yes	Low	48	135,62	106.23	158.60	275.51	324.02
B3	Medium	Yes	High	31	98,76	127.20	126.90	252.90	394.23
B4	Good	Yes	High	39	128,60	112.20	129.20	285.01	344.99
B5	Medium	Yes	Low	33	27,26	37.61	45.29	249.20	640.64
B6	Medium	No	High	26	38,20	53.08	59.28	184.70	664.80
B7	Medium	No	Low	36	26.59	38.79	47.53	222.56	664.50
B8	Good	No	High	45	40.03	58.87	47.62	235.80	617.66
B9	Medium	No	Low	41	54.10	73.02	121.30	494.00	257.52
B10	Medium	Yes	High	25	61.00	40.97	154.92	502.19	240.92
B11	Medium	Yes	High	36	58.60	67.08	130.93	487.70	255.67
B12	Not done	Not done	Not done	Not done	56.31	40.09	150.95	491.12	261.51
B13	Medium	No	Low	49	80.80	120.24	135.20	233.60	424.50
B14	Bad	No	High	55	88.48	141.10	156.80	193.40	420.10
B15	Medium	No	Low	38	83.31	117.89	152.09	202.61	444.00
B16	Medium	Yes	Low	46	68.67	101.26	132.53	217.80	479.74
B17	Bad	Yes	Low	30	16.70	58.71	60.40	215.40	648.77
B18	Medium	Yes	High	48	40.00	39.30	70.90	173.83	676.00
B19	Medium	No	High	33	18.81	56.73	65.03	205.90	653.52
B20	Bad	Yes	Low	31	20.58	36.71	62.41	191.18	669.10
B21	Bad	Yes	Low	54	54.10	85.60	111.28	443.50	305.40
B22	Bad	Yes	Low	43	56.97	129.70	98.80	470.30	244.23
B23	Medium	No	Not done	52	59.80	120.60	108.43	510.50	200.67
B24	Bad	Yes	Low	43	77.15	91.41	113.57	466.61	251.26
B25	Bad	No	High	34	54.10	73.02	121.30	494.00	257.52
B26	Bad	Yes	Low	Not done	Not done	Not done	Not done	Not done	Not done

Table 3. Soil and indoor radon concentrations in Boundiali and assessment of their corresponding qualitative and quantitative risks Site

	Soil radon concentration (kBq/m^3)	Soil radon risk	Indoor radon concentration (Bq/m^3)	Radon effective dose (mSv)	ELCR-EPA	ELCR-UNSCEAR
B1	23 ± 11	Moderate	461 ± 200	12 ± 5	278 – 876	369 – 1014
B2	10 ± 4	Low	221 ± 94	6 ± 3	133 – 420	177 – 486
B3	26 ± 12	Moderate	263 ± 119	7 ± 3	158 – 500	210 – 579
B4	26 ± 12	Moderate	263 ± 119	7 ± 3	158 – 500	210 – 579
B5	16 ± 7	Slightly moderate	714 ± 300	18 ± 8	430 – 1357	571 – 1571
B6	20 ± 9	Moderate	273 ± 125	7 ± 3	164 – 519	218 – 601
B7	21 ± 10	Moderate	269 ± 121	7 ± 3	161 – 511	215 – 592
B8	35 ± 17	Very moderate	310 ± 140	8 ± 4	186 – 589	248 – 682
B9	16 ± 7	Slightly moderate	109 ± 39	3 ± 1	65 – 207	87 – 240
B10	16 ± 7	Slightly moderate	281 ± 126	7 ± 3	169 – 534	225 – 618
B11	14 ± 6	Slightly moderate	543 ± 240	14 ± 6	327 – 1032	434 – 1195
B12	16 ± 7	Slightly moderate	Not done	Not done	Not done	Not done
B13	27 ± 13	Moderate	741 ± 333	19 ± 9	445 – 1408	593 – 1630
B14	32 ± 15	Very moderate	284 ± 128	7 ± 3	170 – 540	227 – 625
B15	38 ± 18	Very moderate	240 ± 108	6 ± 3	144 – 456	192 – 528
B16	10 ± 4	Low	273 ± 125	7 ± 3	164 – 519	218 – 601
B17	17 ± 8	Slightly moderate	270 ± 121	7 ± 3	162 – 513	216 – 594
B18	13 ± 6	Slightly moderate	284 ± 128	7 ± 3	170 – 540	227 – 625
B19	7 ± 3	Low	155 ± 70	4 ± 2	93 – 295	124 – 341
B20	14 ± 6	Slightly moderate	446 ± 201	11 ± 5	268 – 847	357 – 981
B21	12 ± 5	Slightly moderate	429 ± 187	11 ± 5	257 – 815	343 – 944
B22	15 ± 7	Slightly moderate	179 ± 82	4 ± 2	107 – 340	143 – 394
B23	13 ± 6	Slightly moderate	233 ± 99	6 ± 3	140 – 443	186 – 513
B24	40 ± 19	Slightly high	266 ± 119	7 ± 3	160 – 505	213 – 585
B25	45 ± 22	Slightly high	243 ± 109	6 ± 3	146 – 462	194 – 535
B26	7 ± 3	Low	444 ± 200	11 ± 5	266 – 844	355 – 977

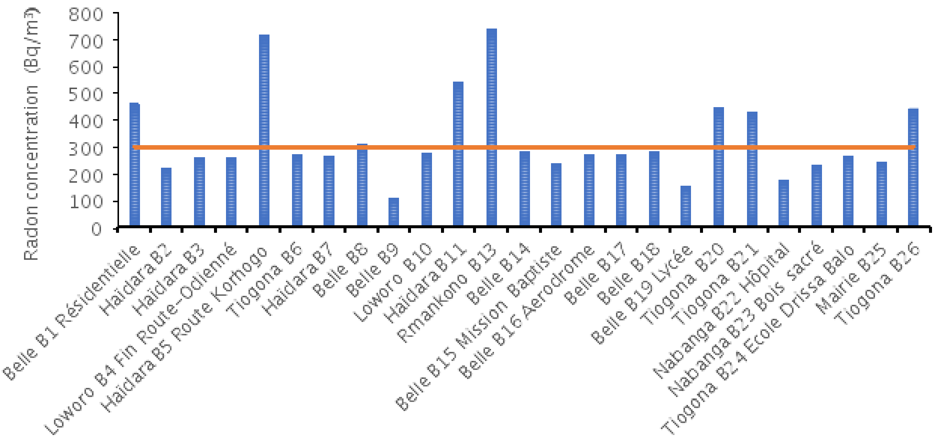

Figure 6. Distribution of indoor radon concentration at the sites of Boundiali compared to ICRP reference level (horizontal line)

4. Conclusion

In this study, the results of integrated measurements carried out in the city of Boundiali show a significant presence of radon. Some values of concentrations of this gas in houses and soils exceeded the standards recommended by the ICRP and WHO regarding the limits in the air and the soil. This could be due to the granitic nature of the soil on the one hand but also to its porosity and particle size composition and the architectural characteristics of houses such as the floor levels on the ground, cracks in the walls, and poor indoor ventilation. However, further investigations using an active detector are necessary and crucial at all sites where high radon concentrations were measured in order to determine radon prone-areas. In addition, the population and the public authorities should be informed about the existence of this gas so that they can take appropriate measures to protect people and reduce the risk that it poses. This study must be extended throughout the country to cover more areas with a particular focus on risk areas such as those with granitic soils. The ultimate goal is to establish a national radon mapping to prevent and mitigate this risk.

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Author Contribution

Agba Dabo Salif Ignace did detectors exposure and analysis and he conceived and wrote up the article. All the co-authors did the article proofreading. Gogon Bogbe Douo Huberson and Anouan Koutoua Joseph did data collection. Koua Aka Antonin did the supervision of detectors exposure and data collection. Mounir Aïtziane collaborated to detectors analysis and Zohra Lounis Mokrani supervised detectors analysis.

Data Availability

The data used in this article are available from the corresponding author upon request.

Declarations

Competing Interests: The authors declare that there are no competing interests.

Ethics approval: This article does not contain any studies involving human or animal subjects.

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