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Quantifying indoor radon levels and determinants in schools: A case study in the radon-prone area Galicia–Norte de Portugal Euroregion

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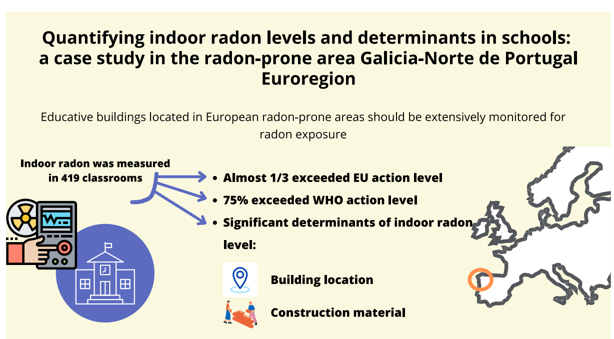
HIGHLIGHTS

- Children and teachers may be exposed to radon at school even longer than at home.
- Euroregion Galicia–Norte de Portugal has extensive radon-prone areas.
- 1/3 of the classrooms exceeded the European Union reference value for radon.
- Classroom and building characteristics explain around 50 % of the indoor radon level.
- Protocol for radon sampling in school buildings should be developed.

GRAPHICAL ABSTRACT



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ABSTRACT

Radon is a carcinogenic compound, and is particularly concerning in the education sector, where children and teachers may be exposed even longer than at home. Thus, this study intended to characterise radon in the indoor air of scholar environments in different provinces/districts of the Euroregion Galicia–Norte de Portugal. With a pioneering approach, this study evaluated the influence of specific factors/characteristics (location, type of management, construction material, season and floor within the building) and quantified their relative contribution to indoor radon levels. Radon was continuously monitored in 416 classrooms from school buildings located in urban and rural sites from different provinces/districts both in the regions of Galicia (A Coruña and Lugo provinces) and Portugal (Porto and Bragança districts), considering rooms for different age groups (from nursery schools to universities). Single and multivariate linear regression models were built considering the radon concentrations as the outcome variable and different room/building characteristics as predictor variables. Mean and median radon concentrations were 332 Bq·m^{-3} and 181 Bq·m^{-3}, respectively. The radon concentrations observed are a public health concern, as almost 1/3 of the places monitored exceeded the reference limit value of the European legislation (300 Bq·m^{-3}). Moreover, around 50 % of the indoor levels measured could be attributed to room/building characteristics: the building's location and the main construction material, as well as the occupants' age group, the floor within the building and the school's type of management (public/private). This study concluded that radon testing is needed in all school buildings and classrooms without exceptions. Thus, public administrations are urged to dedicate funds for testing,

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mitigation and public dissemination initiatives in schools. A special protocol for radon sampling in school buildings should also be developed.

1. Introduction

The interest in indoor air studies has been steadily growing in recent years due to its adverse impact on health (Branco et al., 2020). People spend most of their time indoors, and the levels of some air pollutants are higher indoors than outdoors (Branco et al., 2019; Nunes et al., 2016; WHO, 2010). This is the case of radon, which is one of the key indoor air pollutants (ICRP, 2014; WHO, 2009).

Radon (radon-222) is a colourless, odourless and tasteless natural radioactive gas originated in the decay of uranium that is found in soil and rocks, travels through the soil and enters buildings though cracks in the foundations or, at a lesser extent, from building materials. Radon is a carcinogenic compound being the second cause of lung cancer after smoking in the general population, and the main cause of lung cancer among never-smokers (Barros-Dios et al., 2012; Lorenzo-González et al., 2019). There is no known safe exposure level in the living environment for humans (WHO, 2009), and vulnerable groups of the population like children (Su et al., 2022) are deemed particularly vulnerable because their cells are dividing at a higher rate than adults. The risk of developing lifetime lung cancer due to radon exposure during childhood may be up to three-fold higher than that during adulthood, due to the morphometric differences between the lungs of children and the lungs of adults, as well as higher respiration rates of children compared with adults (Chen, 2013). Children's breathing height is also closer to the exposure source (buildings' floor) than that of adults, which may lead to higher inhaled doses.

Radon is present in all buildings and underground locations. While radon has been extensively studied in dwellings, and particularly in Galicia (Barros-Dios et al., 2007; Darby et al., 2005; Lorenzo-González et al., 2017; Torres-Duran et al., 2014), school buildings have been usually less studied despite their potential adverse consequences on children. School buildings are indoor environments of particular interest regarding radon for several reasons. On the one side, because of the large period of time spent in these buildings, and on the other side because children are a vulnerable group of the population. Moreover, children are frequently physically active in school increasing their inhalation rates and thus the inhaled dose of air pollutants' concentrations. Besides children, from infants to teenagers and young adults, schools are also workplaces for teachers and staff, who might spend even more time in school buildings than children. Schools are generally attended part time; therefore, the long-term average may differ from the average occupancy hours (generally it overestimates the actual radon exposure of children and staff). Additionally, schools are usually more complex buildings than households, which difficult monitoring and the implementation of mitigation measures. Many schools in Europe, particularly those located in city centre, are old buildings without mechanical ventilation systems and worse isolation from the ground.

Although radon is ubiquitous inside the school building, levels can vary considerably from location to location depending on several factors already reported in the literature, including occupancy regimes, ventilation and the use of Heating, Ventilation and Air Conditioning (HVAC) systems, year of building's construction, construction features including foundation wall construction material, classroom floor level and the absence of underground floors (Ali et al., 2018; Azara et al., 2018; Bochicchio et al., 2014; Branco et al., 2016; Davis et al., 2020; Müllerová et al., 2019; Zhukovsky et al., 2018).

One of the biggest challenges related to radon exposure in school buildings is the cost of testing and mitigation (Gordon et al., 2018). Thus, understanding the building and/or room characteristics that influence radon concentrations is important to define special protocols of measurement in school buildings, and to develop better targeted mitigation measures. Previous studies performed in Spain have shown that >22 % of radon measurements in the education sector had results upper than 300 $Bq{\cdot}m^{-3}$ (Ruano-Ravina et al., 2019).

Despite the major relevance of studying indoor radon in school buildings, literature is still scarce and scattered, recognising that more studies are still needed. Namely, there is a limited number of studies in school buildings when compared with households and workplaces, despite children's higher vulnerability. Additionally, none or very few studies considered school buildings including all the age groups, from nursery (infants) and primary schools (children), to secondary (teenagers) and even university (young adults) using the same methodology. Likewise, the quantification of the contribution of building characteristics to indoor radon concentrations has been limited (Branco et al., 2016). Moreover, approaches to radon testing varied considerably by province and region (Shergill et al., 2021), which biases the comparison between provinces/regions. Additionally, there is a lack of representative data which makes extrapolation usually speculative (Zhukovsky et al., 2018). Also, building characteristics and materials may differ from one region or country to another. Finally, the number of studies performed in education buildings located in radon-prone areas is still scarce.

Thus, the main objective of this work was to characterise indoor radon of scholar environments in different provinces/districts of the Galicia–Norte de Portugal Euroregion, by evaluating the influence of specific factors/characteristics and quantifying their relative importance to indoor radon levels in school buildings (location, type of management, construction material, sampling season and floor within the building).

2. Materials and methods

2.1. Study sites

This study was conducted in the Galicia–Norte de Portugal Euroregion, which is a cross-border Euroregion straddling Galicia (Spain) and the Norte de Portugal Region (Portugal) with a common heritage, a very close language and similar lifestyle habits. It was conducted in different educational facilities considering different age groups, namely: nursery schools (<3 years old), preschools/kindergartens (3–5 years old), primary school (6–10 years old), secondary school (12–18 years old) and high school/professional training (young adults).

School buildings in different provinces/districts both in Galicia (A Coruña and Lugo provinces) and Norte de Portugal (Porto and Bragança districts), with both public and private management, as well as urban and rural locations were considered. Buildings at the same location and context were assumed to have their foundations in similar predominant rock type in the soil, given their proximity. Schools from Galicia were included following a convenience sampling consisting on schools that proactively requested measurements to the Galician Radon Laboratory (University of Santiago de Compostela).

Radon in indoor air was sampled in multiple classrooms in each of the studied buildings, considering rooms in different floors. In the case of Galician schools, within each building, sampling was planned and performed following the competent authority guideline GS11.04 on Methodology for occupational radon evaluation (Consejo de Seguridad Nuclear, 2012). In the case of Portuguese schools, sampling was planned following the methodology for evaluation of IAQ in commercial and service buildings proposed by the competent national authority in the scope of the legislation (Portaria 353-A/2013).

A total of 416 rooms were included in this study. In a prior inspection to each room/building, direct observations and interviews with the staff allowed to capture relevant information on building and room characteristics, namely core construction material (stone or brick), room floor, and age group of the occupants.

Table 1
Summary of the main characteristics of the studied classrooms (n = 416).

Characteristic	% of classrooms
Location	
A Coruña province (urban locations)	55.8
A Coruña province (rural locations)	15.4
Bragança district (rural locations)	5.3
Lugo province (rural locations)	7.2
Porto district (urban locations)	16.3
Type of management	
Public	64.9
Private	35.1
Construction material	
Brick	67.5
Stone	32.5
Season of sampling	
Cold	18.3
Warm	81.7
Floor	
−2	2.2
−1	7.5
Ground floor	47.6
1	29.3
2 or higher	12.0
NA	1.4
Age group of the occupants	
Infants	3.8
Children	57.7
Adolescents	30.5
Adults	7.9

2.2. Indoor radon sampling

Radon in indoor air of classrooms was sampled continuously using passive or active detectors. Passive detectors used were alpha track radon detectors. These devices were read at the Galician Radon Laboratory (www.radon.gal), which was certified by the Spanish National Entity of Accreditation in 2019. Radim 5B radon monitor (SMM, Prague, Czech Republic) was one active radon detector used. This radon monitor measures the α-activity of radon decay products (^{218}Po and ^{214}Po) collected from the detection chamber on the surface of a semiconductor detector by an electric field. This radon monitor was calibrated by the manufacturer by placing it in a barrel (controlled atmosphere) next to a reference instrument and CAL factor of the calibrated equipment was modified to get the same result as in the reference instrument. Calibration precision was about 5 %. The error of the equipment is 5 % for concentrations above 80 Bq·m^{-3}, and 20 % for concentrations below that. In some cases, Sarad Scout instruments (SARAD GmbH, Germany) were also used to obtain hourly radon concentrations. These devices use scintillation chamber to detect radon and thoron. They were calibrated by the manufacturer and are periodically tested in different radon conditions (low, medium and high radon conditions). The Galician Radon Laboratory is also certified by the Spanish National Entity of Accreditation for continuous radon measurements.

Radon detectors were placed inside the studied classrooms as close to the centre of the room as possible, far from windows, doors and room's corners, approximately at the same height of children's breathing zone (1.5 ± 0.5 m). Depending on secured permissions from school's administration, and due to financial constraints, samplings with active detectors were performed for at least 2 consecutive working days in each room. Alpha track detectors were placed during at least 3 months.

2.3. Data analysis

Descriptive statistics were initially performed. The arithmetic mean in each classroom was calculated using the radon concentrations obtained with the active detector. Histograms and boxplots were drawn to help visualise the data collected. Normality of the distributions was assessed using the Shapiro-Wilk and Anderson-Darling normality tests. The strength of the relationship between two categorical variables was evaluated using Cramers' V.

Radon concentrations in the studied indoor environments were compared with the reference level for occupied buildings in the study region (300 Bq·m^{-3}) to calculate exceedances. Although there is no safe threshold below which radon will not have any negative effect on human health, this reference limit resulted from the translation of the European Directive (Council Directive 2013/59/Euratom of 5 December 2013) to the Spanish legislation in the case of Galicia (Real Decreto 1029/2022, de 20 de diciembre) and to the Portuguese legislation in the case of Norte de Portugal (Decreto-Lei n.° 108/2018, de 3 de dezembro).

Aiming to quantify the determinants of radon concentrations, single and multivariate linear regression models were built considering the radon concentration as the outcome variable and potential determinants (room or

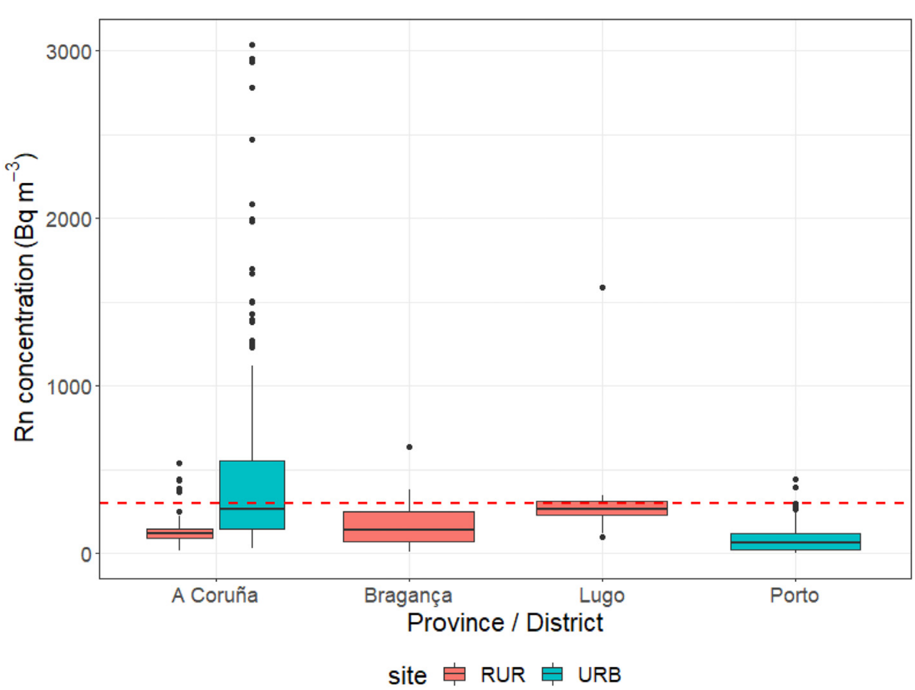

Fig. 1. Radon concentrations by location (province/district) and context (urban/rural).

building characteristics that may influence radon concentration) as predictor variables. Bivariate analysis was conducted by either the non-parametric Wilcoxon Rank Sum test (also called Mann-Whitney *U* test) and Kruskal-Wallis test, and by simple linear regression modelling. Radon concentration was considered as the outcome variable, while room and building characteristics were considered as predictors. Variables that yielded a significant *p*-value in the bivariate analysis were selected to enter the multivariate linear regression model. Standard post-diagnostic tests were run on the final model distribution of the residuals. The relative importance of the predictors was estimated in the multivariate models.

The level of statistical significance was set at 0.05. Statistical analysis was performed with R software, version 4.2.0.

3. Results

3.1. Characterisation of indoor radon concentrations

Table 1 summarises the main characteristics of the studied indoor microenvironments (classrooms). The majority of the studied classrooms were from public schools, occupied by children aged 3–12 years old, and predominantly located in the ground floor (47.6 %) and first floor (29.3 %). The majority of the classrooms studied were located in urban sites from A Coruña province, while <10 % of the studied classrooms were located in rural locations from Bragança district or Lugo province.

In the studied classrooms, the mean indoor radon concentrations varied from 3 Bq·m^{-3} to 3039 Bq·m^{-3}, with median, geometric and arithmetic mean being, respectively, 181 Bq·m^{-3}, 185 Bq·m^{-3} and 332 Bq·m^{-3}. The histogram with the distribution of the radon concentrations can be seen in Supplementary Material (Fig. S1).

The distribution of radon concentrations by location (province/district, urban/rural locations) was plotted in Fig. 1. The highest concentration was registered at the urban locations of A Coruña province, while the lowest concentration was registered at Porto district (urban locations). The highest variability in radon concentrations was also found at the urban locations of A Coruña province. This may have occurred as there were more sampling sites in A Coruña province than in any other province/district studied.

Fig. 2 shows the radon concentrations distributed by floor of the studied room within the building. Due to their proximity to the source on soil, and as expected, radon concentrations were higher in underground floors.

Fig. 3 represents radon concentrations by building's predominant construction material. In this study, buildings were broadly classified as brick or stone, considering the predominant construction material. Radon concentrations were higher in predominantly stone-built school buildings.

Radon concentrations in classrooms were plotted according to the school's type of management (public or private) in Fig. 4. Radon concentrations were higher in classrooms from private schools than in those from public schools.

Fig. 5 summarises radon concentrations by season of sampling. Results showed that the variability of radon concentrations was higher in warm than in cold season, and the highest concentrations were registered during warm months (April to September). However, despite the overwhelming majority of samplings (81.7 %) were performed in warm season, median radon concentrations in warm (192 Bq·m^{-3}) and cold seasons (167 Bq·m^{-3}) were similar.

Fig. 6 summarises radon concentrations by age group of the classroom occupants. Age group of the occupants can be seen here as a surrogate measure of activities and occupancy patterns. Globally, lower concentrations were found in classrooms occupied by the youngest (infants), children up to 3 years old. In average, higher concentrations were found in classrooms occupied by adults (>18 years old) in high schools, university and professional training buildings. Radon concentrations had the highest variability and registered the highest values in classrooms occupied by children (aged 6–12 years old), which was expected as the majority (57.7 %) of the classrooms studied were occupied by this age group.

3.2. Comparison with reference limit value

The measured radon concentrations exceeded the reference limit value of 300 Bq·m^{-3} in 30 % of all the studied classrooms, and 31 % of the buildings had at least one room exceeding that threshold. Radon concentrations

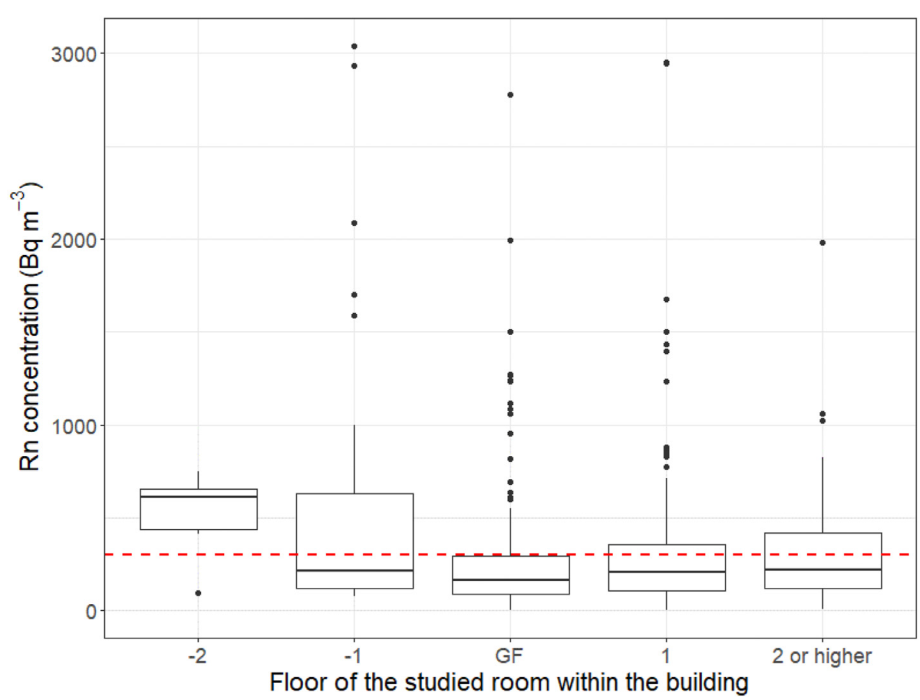

Fig. 2. Radon concentrations by floor of the studied room within the building.

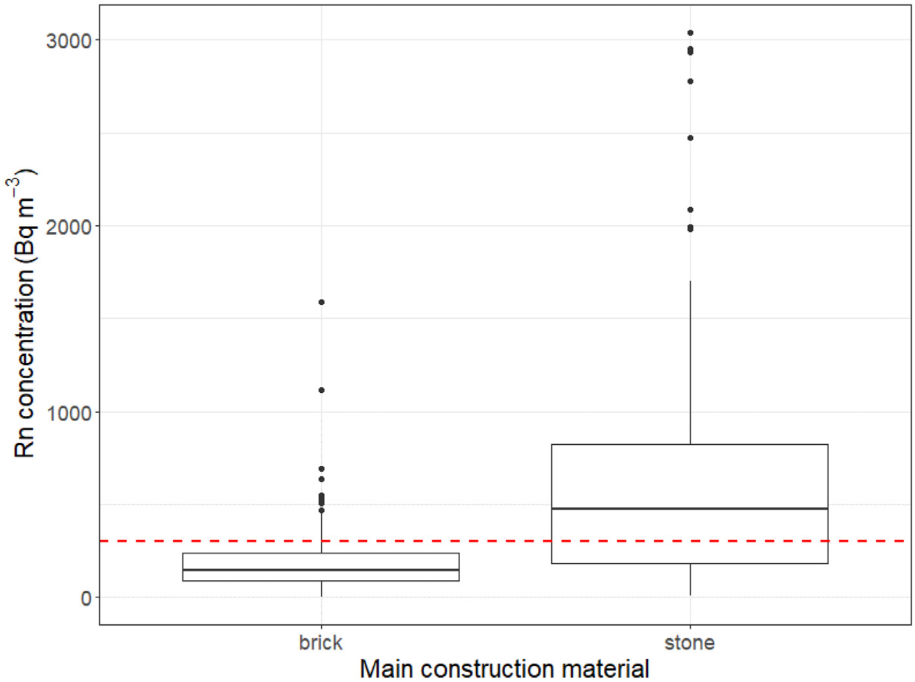

Fig. 3. Radon concentrations by main construction material.

exceeded the reference limit value in all the studied locations, in both public and private schools, in both brick and stone buildings, in both seasons, and in classrooms from all the studied floors and for all the studied occupants' age groups. However, in some cases the percentage of measured concentrations exceeding the reference limit value was higher than in others.

Those exceedances were more frequent in urban locations from A Coruña province (45 %) and in rural locations from Lugo province (30 %) than in the other studied locations (<10 % in each). The registered radon concentrations exceeded the reference limit in more than half of the studied classrooms from private schools (51 %), while in the studied classrooms from public schools the percentage of exceedances was significantly lower (18 %). The proportion of classrooms exceeding the reference limit was also high in buildings mainly built of stone (65 %), while in those of brick that proportion was much lower (12 %).

The percentage of classrooms sampled in warm season exceeding the reference limit value (32 %) was higher than the percentage of classrooms sampled in cold season exceeding the same reference limit (17 %).

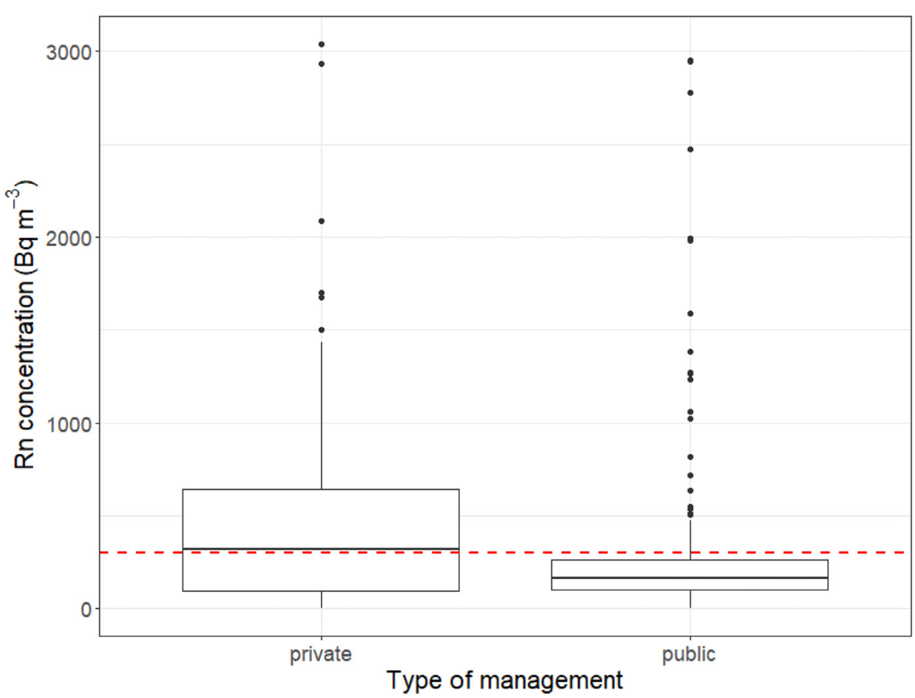

Fig. 4. Radon concentrations by type of management of the school.

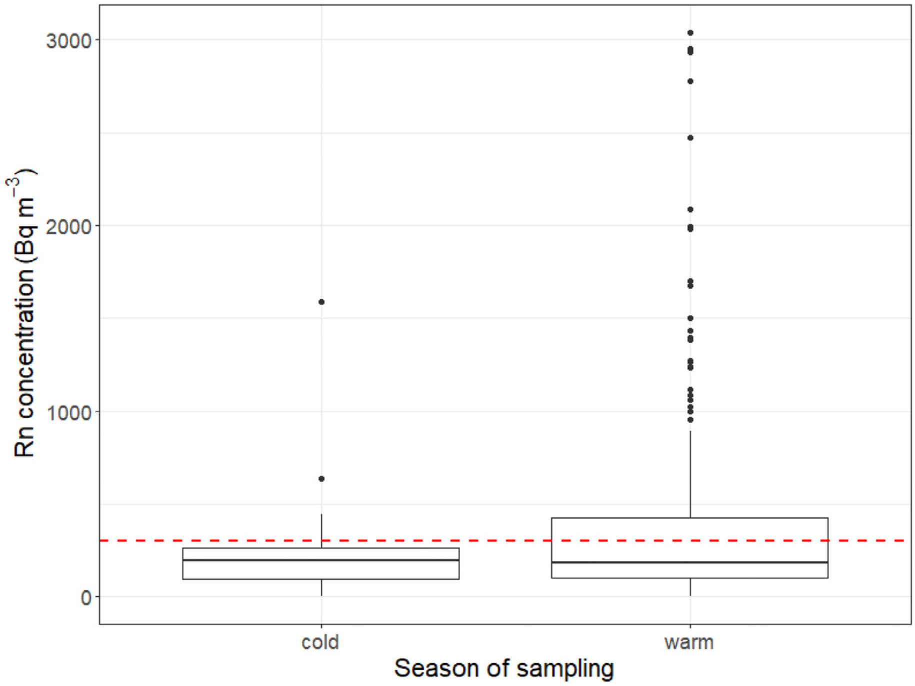

Fig. 5. Radon concentrations by season of sampling.

The percentage of classrooms exceeding the reference limit value was also higher in classrooms located in underground floors (89 % of those located in −2, and 45 % of those located in −1), than in ground and upper floors (23–32 %).

While only 6 % of the studied classrooms for infants exceeded the reference limit value, the percentage of classrooms exceeding that limit was higher among the studied classrooms for children (37 %), followed by those for adolescents (12 %) and for adults (55 %).

3.3. Quantification of indoor radon determinants

Considering indoor radon concentration as the outcome variable, bivariate analysis was performed for each of the main building and classrooms characteristics, using both statistical tests (Table 2) and simple linear regression (Supplementary Material, Tables S1 to S6). This aimed to assess if each of those characteristics were individually potential determinants of the indoor radon concentrations.

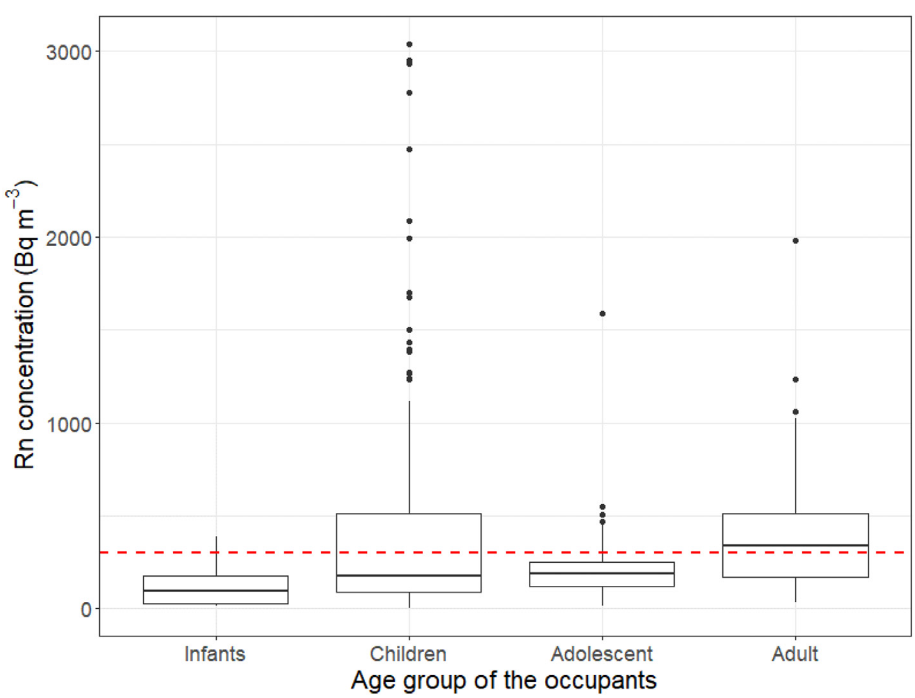

Fig. 6. Radon concentrations by age group of the occupants.

Table 2
Summary of the bivariate statistical tests, considering radon concentration as outcome variable.

Variable	Statistical test	*p*-Value	Significant?
Location	Kruskal-Wallis rank sum test	<0.001	Yes
Type of management	Wilcoxon rank sum test	0.001	Yes
Construction material	Wilcoxon rank sum test	<0.001	Yes
Season of sampling	Wilcoxon rank sum test	0.08	No
Floor	Kruskal-Wallis rank sum test	0.001	Yes
Age group of the occupants	Kruskal-Wallis rank sum test	0.001	Yes

The results of the bivariate analyses evidenced that all the studied building/classroom characteristics had a statistically significant relationship with the indoor radon concentrations measured, with the exception of season of sampling that was not statistically significant (p-value = 0.08) in the bivariate statistical tests results (Table 2) although statistically significant (p-value = 0.04) in the simple linear regression. From these results, none of those studied characteristics (location, type of management, construction material, season of sampling, floor and age group of the occupants) were excluded for the multivariate analysis.

Nevertheless, to avoid collinearity in the multivariate model, predictor variables highly correlated with any of the others had to be excluded. Thus, correlations between all pairs of categorical variables were calculated and summarised in a correlation matrix (Supplementary Material, Table S7). Season of sampling evidenced strong correlation (0.80) with location variable. Due to this, and as the overwhelming majority of the samplings (81.7 %) occurred in warm season, season of sampling variable was not considered in the multivariate model.

Table 3 summarises the results of the multivariate linear regression model considered, including the relative importance of each predictor variable. Results evidenced that this model was statistically significant, indicating that the combination of these variables had a linear effect on radon concentrations. From the studied predictor variables, location had the highest relative importance (54.2 %), followed by construction material (30.5 %). Age group of the occupants (6.6 %), floor (4.7 %) and type of management (4.0 %) were those with the lowest relative importance. Type of management was the variable with the lowest relative importance in the multivariate model, and there was little or no evidence of its association with radon concentrations (p-value = 0.13). Results from the post-diagnostic tests were summarised in Supplementary Material (Table S8), and did not evidence collinearity problems in the model.

4. Discussion

This study adds new findings to the state-of-the-art by characterising indoor radon in school facilities for different age groups (from nursery schools to universities) and located in different provinces/districts of the same Euroregion but overall defined as a radon-prone area. Moreover, as far as authors' knowledge goes this is the first study to quantify the determinants and their relative contribution for radon indoor concentrations in scholar environments. The main conclusion is that educative buildings located in European radon-prone areas should be extensively monitored for radon exposure.

Radon levels found are of public health concern. Although there is no safe threshold below which is safe for human exposure, almost 1/3 of the places monitored exceeded the reference limit value of 300 Bq·m^{-3}. Moreover, around 75 % of the places monitored exceeded 100 Bq·m^{-3}, which WHO recommended as an action level from a public health perspective. This is of major relevance for public health, as schools are susceptible targets, because of the children (vulnerable population) and of the long daily stay. This highlights the need for the implementation of mitigation interventions to reduce radon exposure and highlights that new educative buildings should follow tightly the construction codes avoiding high radon concentrations.

Mean and median radon concentrations in the present study were higher than those observed in the literature. Comparison with the literature should be made carefully, due to the methodological differences in studies. Szabados et al. (2021) reported mean and median concentrations of, respectively, 98 Bq·m^{-3} and 55 Bq·m^{-3}, in schools from 5 Central European countries (Czech Republic, Hungary, Italy, Poland and Slovenia). This study also observed that radon concentrations varied markedly across the investigated sites. Kojo and Kurttio (2020) reported radon concentrations in Finnish daycare centers and schools (mean 82 Bq·m^{-3}; median 41 Bq·m^{-3}), and found less exceedances than the present study to the 300 Bq·m^{-3} reference level (exceeding only in 8 % of the daycares and in 14 % of the schools). Median radon concentration in the present study was also higher than that found by Azara et al. (2018) in primary, secondary and tertiary schools in a city located in the Midwest of Italy (91.6 Bq-m^{-3}). Moreover, mean radon concentration in the present study was also higher than that earlier found in nursery and primary schools by Branco et al. (2016) in nursery and primary schools from Norte de Portugal region (37–275 Bq·m^{-3}), and by Sá et al. (2017) and by Sousa et al. (2015) in nursery schools in the same region. Also compared to the worldwide population weighted radon concentration in kindergartens

Table 3
Results of the multivariate linear regression model, considering radon concentration as outcome variable and room/building characteristics as predictor variables.

	Coefficient (β)	95 % CI	SE	*t* value	*p*-Value	Relative importance
Intercept	2.04	1.89, 2.19	0.08	26.25	<0.01*	
Floor						4.7 %
floor_new.L	0.02	−0.15, 0.19	0.09	0.20	0.84	
floor_new.Q	−0.07	−0.21, 0.07	0.07	−0.94	0.35	
floor_new.C	0.16	0.04, 0.28	0.06	2.63	0.01*	
floor_new^4	−0.06	−0.14, 0.02	0.04	−1.49	0.14	
Type of management						4.0 %
Public (*ref.* private)	−0.08	−0.19, 0.02	0.05	−1.53	0.13	
Construction material						30.5 %
Stone (*ref.* brick)	0.44	0.34, 0.54	0.05	8.36	<0.01*	
Age group of the occupants						6.6 %
.L	−0.07	−0.25, 0.11	0.09	−0.78	0.44	
.Q	−0.17	−0.30, −0.05	0.06	−2.70	0.01*	
.C	−0.06	−0.14, 0.02	0.04	−1.47	0.14	
Location						54.2 %
A Coruña province (urban locations) (*ref.* A Coruña province (rural locations))	0.24	0.13, 0.35	0.06	4.35	<0.01*	
Bragança district (rural locations) (*ref.* A Coruña province (rural locations))	−0.08	−0.26, 0.11	0.09	−0.82	0.41	
Lugo province (rural locations) (*ref.* A Coruña province (rural locations))	0.34	0.19, 0.50	0.08	4.41	<0.01*	
Porto district (urban locations) (*ref.* A Coruña province (rural locations))	−0.45	−0.59, −0.31	0.07	−6.20	<0.01*	

Multiple R^2 = 0.52; Adjusted R^2 = 0.50; AIC = 294.35.
* p-Value < 0.01.

and schools (arithmetic mean 59 and geometric mean 36 Bq·m^{-3}) calculated with the 63 national and regional surveys reviewed by Zhukovsky et al. (2018), the concentrations in the present study were higher.

The results from the present study confirmed that some building and room characteristics are significant determinants of indoor radon concentrations in schools, particularly building's location and the main construction material. Although building location was a main determinant, this may have occurred because of the predominant soil characteristics and not merely dependent of the context (urban/rural). Moreover, with a lower contribution, the age group of the occupants, the floor of the room, and the school's type of management were also determinants of indoor radon concentrations in schools. These factors altogether explained around 50 % of the indoor radon concentrations found.

Zhukovsky et al. (2018) observed higher indoor radon concentrations in children's institutions in comparison with those in dwellings, which could probably be explained by the characteristics of ventilation, attendance regime and construction features of schools. In the study by Azara et al. (2018) radon concentration was significantly correlated with the number of occupants (students and teachers), the foundation wall construction material, and with the absence of underground floors. Radon measurements in four kindergartens in Slovakia performed by Müllerová et al. (2019) evidenced daily and annual variations, and those daily variations strongly depended on the ventilation of rooms. The contribution of ventilation was also recently highlighted by Davis et al. (2020) in Utah's public schools, USA. They found that: i) the installation of HVAC system and the number of students was inversely associated with having classroom radon concentrations at or above the Environmental Protection Agency (EPA) recommended action level of 148 Bq·m^{-3}; and ii) classroom radon concentrations decreased when schools' HVAC systems were on. Previously, Branco et al. (2016) have also concluded that the measured concentrations in nursery and primary schools depended on the building occupation, classroom floor level and year of the building's construction. Thus, the results from the present study not only confirmed and quantified the relevant contribution of some of the building/room characteristics (building's location, main construction material and floor of the room within the building), as they identified other contributors which have been usually neglected and whose contributions were never quantified (age group of the occupants and school's type of management — public vs. private).

Although this study considered several building/room characteristics inclusively in multivariate models, there are other building/room characteristics that were not possible to evaluate although there was already some evidence of their contribution to indoor radon concentrations, namely ventilation, occupant density or age of the building.

The results of the present study demonstrated the societal relevance of understanding radon in indoor air of school buildings. This information is key not only for scientific and technical communities in indoor air studies, but also to decision-makers and school building managers responsible for protecting people's health. The results of the present study also evidence that concerted policies are needed between the governing bodies of Norte de Portugal and Galicia with regard to population protection to radon exposure. Radon in buildings does not recognise administrative boundaries. Radon testing/screening should be done in all school buildings, even in those located outside the risk areas identified in radon risk maps or in expected radon-prone areas. While radon testing is cheap, mitigation can be costly, thus governments should develop and fund initiatives to protect children and schools' staff health. Some examples of state/governmental funding for testing, mitigation, and public dissemination of radon levels in schools in the USA were reviewed by (Gordon et al., 2018). The emergence of novel continuous active low-cost sensors can also contribute to make indoor air radon monitoring ubiquitous by reducing its costs (Barros et al., 2021; Chojer et al., 2020; Ródenas García et al., 2022; Sá et al., 2022). Given their singularities in comparison with other buildings, a special protocol of radon measurement in scholar buildings is required, as previously stated by (Zhukovsky et al., 2018).

Despite the relevance of the results, this study has limitations. The main one is the limited number of indoor measurements for such a large and populated area. Nevertheless, authors believe that the education facilities included in this study are representative of the whole study area as it included buildings located in different urban and rural locations, and included all education levels (from nursery to university). In fact, it is worth mentioning that the overwhelming majority (~94 %) of the stone buildings studied were located in urban sites. Although this can be seen as a study limitation, it reflects the reality in Spain and Portugal, and probably in Europe, as many schools in urban sites are located in old historic buildings, many of them originally built for other purposes. Another limitation is having used both active and passive radon sampling, though other studies have observed that they are highly comparable.

This study also has strengths. All radon measurements had high quality, and the fact of presenting an intercountry collaboration increases the external validity of the results in the present paper. Having considered school buildings from all educational levels is also a relevant advantage of the present study, particularly nursery schools given the low number of radon exposure studies in that specific education facilities. The inclusion of several different specific factors/characteristics that allowed the use of multivariate modelling also strengthen the present study.

5. Conclusions

This study successfully characterised radon in indoor air of school buildings in different provinces/districts of the Euroregion Galicia–Norte de Portugal, and it was pioneer in quantifying the relative contribution of several determinant factors/characteristics to the indoor radon levels in a recognized radon-prone area.

The results of the present study demonstrate the societal relevance of understanding radon in indoor air of school buildings in order to protect occupants' health. Radon concentrations found were of public health concern, as they were elevated in about 1/3 of the studied rooms. Moreover, around 50 % of the indoor radon levels were determined by room/building characteristics, namely building's location and the main concentration material, as well as the age group of the occupants, the floor of the room and the school's type of management (public vs. private). It is of paramount importance to follow the ALARA principles (as low as reasonably achievable) in all education sector regarding indoor radon concentrations.

This study also concluded that radon testing is needed in all school buildings and classrooms without exceptions, even outside radon-prone areas. To make indoor radon assessment ubiquitous in school buildings, governments should dedicate funds for testing, mitigation and public dissemination initiatives. Moreover, novel emerging low-cost sensing technologies may play a pivotal role in the future of radon exposure assessment. A special protocol for radon sampling in school buildings should also be developed.

CRediT authorship contribution statement

Pedro T.B.S. Branco: Conceptualization, Formal analysis, Software, Visualization, Methodology, Writing – original draft.

Lucia Martin-Gisbert: Data curation, Investigation, Funding acquisition, Reviewing and editing.

Juliana P. Sá: Data curation, Investigation.

Alberto Ruano-Ravina: Conceptualization, Funding acquisition, Project administration, Supervision, Reviewing and editing.

Juan Barros-Dios: Funding acquisition, Resources.

Leonor Varela-Lema: Resources, Funding acquisition, Reviewing and editing.

Sofia I.V. Sousa: Conceptualization, Funding acquisition, Project administration, Supervision, Methodology, Reviewing and editing.

Data availability

The data that has been used is confidential.

Declaration of competing interest

Pedro T.B.S. Branco has no competing interests to declare.
Lucia Martin-Gisbert: has no competing interests to declare.
Juliana P. Sá: has no competing interests to declare.
Alberto Ruano-Ravina: has no competing interests to declare.
Juan Barros-Dios: has no competing interests to declare.
Leonor Varela-Lema: has no competing interests to declare.
Sofia I.V. Sousa: has no competing interests to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.163566.

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