



Radon exposure and its influencing factors across 3,140 workplaces in Spain

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ABSTRACT

Indoor radon exposure increases the risk of lung cancer. Radon concentration in workplaces is regulated in EU countries, including Spain, based on a reference level of 300 Bq/m³. The objective of this study is to describe workplace radon exposure in Spain and its influencing factors. To do this, we collected long-term radon measurements with alpha track detectors in 3140 workplaces mainly located in radon prone areas. Radon concentration exceeded 300 Bq/m³ in 1 out of 5 workplaces. Median radon concentration was 107 Bq/m³ in radon prone areas, 28 Bq/m³ off radon prone areas, and 101 Bq/m³ globally for the complete sample. Our results indicate that excessive radon concentrations can be expected in radon prone areas at all floor levels, especially below ground. Floor level, working sector, and location significantly influence radon concentration. The highest radon concentrations were found in the Education & Culture sector, comprising schools, universities, libraries, or cultural centers. These results indicate that radon should no longer be considered a risk for marginal occupations, but a risk everyone has if located in a radon prone area. Immediate action, including radon testing and mitigation, is needed to protect workers in Spain against radon exposure. This is already mandatory since EU regulation for radon has been recently transposed in Spain. Competent authorities should enforce this regulation without further delay, and employers must address their responsibility and communicate with workers about this risk.

1. Introduction

Lung cancer causes the highest number of cancer deaths worldwide (Sung et al., 2021), and is probably the most avoidable cancer. It is predominantly caused by modifiable agents, namely tobacco use. After smoking, exposure to indoor radon is considered the main risk factor in the general population (World Health Organization, 2009).

Radon is a naturally-occurring radioactive gas originating from uranium decay. Radon emanates from the soil, dilutes in the atmosphere, and remains there in relatively low concentrations. However, radon accumulates in closed spaces such as dwellings or workplaces, sometimes reaching indoor concentrations above WHO or European

Union reference levels: 100 Becquerels per cubic meter (Bq/m³), and 300Bq/m³ respectively (World Health Organization, 2009; European Union, 2013).

When inhaled, radon and its short-term progeny (Polonium 218 and Polonium 214) emit alpha radiation, a type of ionising radiation, which impacts the pulmonary cell lining and could potentially produce carcinogenic DNA mutations (NRC (National Research Council), 1999). Each 100 Bq/m³ increment in radon concentration at home significantly increases lung cancer risk by a 16%, following a linear non-threshold dose-response (Darby et al., 2006). Furthermore, there is a synergistic effect between radon and tobacco smoking (Darby et al., 2006). A linear effect has also been demonstrated for never smokers. Different studies in

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Europe have provided estimations for radon attributable mortality ranging from 3% to 10% of the total lung cancer mortality (Martin-Gisbert, 2022b). In the case of Spain, residential radon accounts for 3.8% of the total lung cancer mortality, with high variability between regions, and reaching 7% in radon prone areas such as Galicia (Ruano-Ravina et al., 2021).

Radon exposure arises from geogenic and anthropogenic factors. Briefly, the amount of uranium in the bedrock and soil permeability determine the potential radon emanation from the soil in a particular geographic area — this is known as the geogenic radon potential (Gruber et al., 2013; Petermann et al., 2021). On the other hand, building's characteristics and use, including ventilation habits, determine radon entry and accumulation indoors (Barros-Dios et al., 2007; Demoury et al., 2013; Yarmoshenko et al., 2016). The latter are modifiable factors that could be considered anthropogenic whereas the geogenic potential is inherent to the location. Thus, to fully assess indoor radon exposure, accurate measurements are needed.

In Spain, the National Radon Potential Map (Consejo de Seguridad Nuclear, 2017) feeds from a 12,000-household-survey, combined with ambient gamma dose rate and geological information (García-Talavera et al., 2013). This map establishes radon prone areas (designated as radon priority areas) as those where 10% or more of the dwellings present radon levels above 300 Bq/m³ at basement or ground floor. In Spain, 17% of the territory is classified as radon prone, with large variations between regions (Consejo de Seguridad Nuclear, 2017). Since 2019, following Directive 2013/59/Euratom, the Spanish Building Code has enacted mandatory radon protection measures for new buildings and rehabilitation, based on a list of radon prone municipalities (Ministerio de Interior, 2019).

Workplace radon exposure is regulated in EU Member states via national transposition of the Directive 2013/59/Euratom on Basic Safety Standards for Ionising Radiation. In Spain, the Directive requirements for workers' radon exposure were transposed only recently, via Royal Decree 1029/2022 in December 2022 (Ministerio de Presidencia, 2022), almost 5 years after expiration of the transposition period established by the European Commission.

Previous national regulation in Spain for occupational radon covered radon exposure only at underground works (such as tunnels or caves) and workplaces processing groundwater, and allowed a reference level of 600 Bq/m³ (Consejo de Seguridad Nuclear, 2011). Moreover, enforcement of this regulation remained poor due to lack of political will and insufficient inspection resources.

By June 2024, in accordance with the new regulation (Ministerio de Presidencia, 2022), also all workplaces at basement level or ground floor in radon prone areas will have to make radon measurements. In workplaces where radon levels are above 300 Bq/m³, remediation in accordance with the optimisation principle is mandatory. If needed, constructive solutions can be combined with technical and operational solutions, including occupancy time restrictions, to reduce workers' exposure (Martin-Gisbert et al., 2022a). Where workers are liable to receive doses above 6 mSv, their exposure needs to be managed as a planned exposure situation (Ministerio de Presidencia, 2022). Noteworthy, radon-exposed workers are recognized as the workforce with the highest exposure to ionising radiation, surpassing even those working in the nuclear sector (UNSCEAR, 2022).

In a previous pilot study, radon concentration was measured in 248 Spanish workplaces, mostly located in radon prone areas, and 27% exceeded 300 Bq/m³ (Ruano-Ravina et al., 2019). This study was the most relevant to date in Spain, with the largest sample of workplaces reported.

Whereas there is available data on residential indoor radon levels from comprehensive surveys, evidence on radon exposure in the workplace is scarce, both in Spain and worldwide. Furthermore, a recent European study observed that workplace radon levels are statistically different to residential ones (Trevisi et al., 2022). Radon exposure at work could be as relevant as residential exposure due to the long time

spent at work. More data and a better understanding of the factors influencing radon levels at the workplace are needed to support tailored interventions.

We hypothesized that a relevant percentage of workers are exposed to radon concentrations above the reference level, considering previous results from the pilot study, and that easy-to-access characteristics of the workplace, such as working sector or location type, could significantly affect the odds of finding high radon concentrations.

The objective of this study is to describe workplace radon exposure in Spain and its influencing factors, aimed at supporting efficient compliance strategies. This objective is in line with United Nations Sustainable Development Goals 8 (target 8.8) and 3 (targets 3.4, 3.9 and 3.d) on decent work and good health.

2. Methods

2.1. Sampling

We compiled all measurements successfully completed in workplaces from 2015 until 2022. These measurements arise from the activity carried by the Galician Radon Laboratory (GRL), meaning that they were performed upon employer's request.

We included only long-term measurements of at least 90 days, carried with passive detectors known as alpha-track detectors CR-39 (Radosys, Inc). Short-term measurements were excluded because the radon concentration assigned to a workplace should provide an estimate of the annual average of radon concentration obtained from a long-term measurement, according to Spanish regulation.

2.2. Radon measurements

All measurements were obtained from the GRL, a certified provider of radon measurements belonging to the University of Santiago de Compostela (Spain). The GRL is accredited for radon measurement using nuclear-track detectors and continuum monitors, according to UNE-EN ISO/IEC 17025:2017, by the Spanish National Entity for Accreditation (ENAC) and follows the applicable requirements from the Spanish Nuclear Safety Council (Consejo de Seguridad Nuclear, 2012). GRL is a non-profit laboratory that has previously provided measurements for numerous research studies, including the European collaborative case-control study on residential radon and lung cancer (Darby et al., 2005).

2.3. Data collection

For each radon measurement at each workplace, 22 variables were extracted to an excel file using anonymized IDs for each worksite and employer. Featured variables were ownership type (public or private), sector, radon potential of the location, urban or rural location, public permanence (yes/no), floor where the detector was placed, season of the measurement, and radon concentration (see Table 1).

2.4. Data analysis

A descriptive analysis was performed to obtain the percentage of workplaces exceeding 300 Bq/m³, and median radon concentration (both globally and sorted by each of the variables included in Table 1).

A bivariate analysis was performed for each of the variables, using radon concentration as the dependent continuous variable. For those variables with numerous categories, namely sector and floor, bivariate analysis results were graphically presented using the tool <https://graphonline.ru/es/>. This visualization was used to better identify relevant clusters of categories to be used in the multivariate analysis.

Multivariate analysis was performed using relevant variables based on the bivariate analysis. A correlation analysis was performed to discard collinearity between selected variables. A linear regression

Table 1
Featured variables extracted and analysed.

Ownership type: private or public
Sector: Education (includes educational, science and sport facilities), Culture (includes libraries, museums, socio cultural centers and institutions, churches, and media), Financial Services (banks), Public Services (public administration offices), Utilities (power plants and water supply infrastructure), Agriculture, Health Services (includes adult day centers), Mining, Retail, Technology (tech companies), Tourism (hotels and balnearies), Transport.
 Source: ad hoc classification based on the International Labour Organization classification and a previous study of occupational radon exposure (Gooding, 2018).
Public permanence: Yes or No. Yes, only if users/members of the public can spend as much time as workers in the measured workplace, e.g.: educational facilities, libraries, adult day center.
Level of urbanization of the location: Urban or Rural. Classified as Urban if the municipality where the workplace is located is classified with Eurostat Degree of Urbanization index (DEGURBA) as a densely populated zone (ZDP) or intermediate zone (ZIP) (Eurostat, 2019).
Radon potential of the location: Yes or No. We tagged as radon prone (radon potential = yes) those municipalities listed on Appendix B of section HS6 of the Spanish Building Code as “zone I” and “zone II” municipalities (Ministerio de Interior, 2019). Municipalities not listed in this appendix were tagged as not radon prone (radon potential = no).
Season: Warm if initial date of measurement was between March and August (both included). Cold if between September and February.
Floor: Underground (from -4 to -1 floor level), ground floor, first floor, second floor, above second floor (from 3rd to 10th floor).
Radon concentration: according to the integrated radon measurement (Bq/m³).

model was applied to selected variables, using radon concentration (Bq/m³) as dependent/outcome variable. We also applied a logistic regression model with the same relevant variables, using as outcome variable radon exceedance categorized as yes or no (using 300 Bq/m³ as the cutpoint). We used SPSS package version 28.

2.5. External dataset: source and analysis

The Spanish Nuclear Safety Council (CSN) provided us with registry-based aggregated data of employers' self-reported radon levels for underground mines and spas in Spain—both sectors are regulated since 2011. This aggregated dataset is based on long-term measurements performed with nuclear track etched detectors. This CSN dataset was not included in our sample and a separate descriptive analysis was performed. This dataset was analysed separately for two reasons: first, workplaces included in this registry are specifically those expected to have higher radon concentrations due to its nature; secondly, this aggregated dataset was not available in detail.

3. Results

3.1. Characteristics of the sample

We collected data for 3140 workplaces located at 253 work centers. The sample included measurements in 14 different provinces of Spain and concentrated in the region of Galicia that accounted for 89% of the workplaces measured.

The main characteristics of the sample are shown in Table 2. Most measurements were from radon prone areas (95%) and urban municipalities (78%). The public sector accounts for 66% of the workplaces measured. Data from a variety of floor levels were collected, and ground level and first floor workplaces represent together 61% of the sample. Forty-two percent of workplaces have public permanence, meaning that users can spend as much time as workers there. Education sector compiled 1268 measurements whereas the mining sector only 7 (included in the “others” category in Table 2).

3.2. Descriptive and bivariate analysis

Twenty percent of workplaces (623) exceeded 300 Bq/m³. Radon

Table 2
Main characteristics of the sample (n = 3140).

Variable Categories	N (%)	Median radon (IQ range) ^e Bq/m ³	% exceeding 300Bq/m ³
Ownership type			
Public	2068 (66%)	112 (208)	21 %
Private	1072 (34%)	91 (147)	17 %
Sector			
Culture ^a	305 (10%)	137 (272)	28 %
Education ^a	1268 (40%)	124 (248)	25 %
Public service	543 (17%)	109 (202)	22 %
Financial services	320 (10%)	97 (73)	5 %
Utilities ^b	518 (16%)	66 (111)	12 %
Other ^{b,c}	186 (6%)	66 (119)	10 %
Public permanence			
yes	1317 (42%)	130 (242)	25%
no	1793 (57%)	92 (154)	16%
n/c	30 (1%)	–	–
Urbanization level			
Urban	2465 (78%)	104 (199)	21%
Rural	675 (22%)	89 (180)	17%
Season			
Cold	756 (24%)	79 (214)	21%
Warm	2384 (76%)	106 (188)	19%
Radon potential			
Not radon prone	161 (5%)	28 (32)	1%
Radon prone	2979 (95%)	107 (201)	21%
Floor level			
Underground	376 (12%)	174 (275)	30%
Ground floor	1072 (34%)	107 (200)	21%
1st floor	676 (22%)	95 (179)	17%
2nd floor	385 (12%)	90 (170)	18%
Above 2nd floor	354 (11%)	95 (116)	17% ^d
n/c	277 (9%)	60 (137)	15%

^a Belongs to “Education and Culture” category, created after clustering sectors (see Fig. 1).

^b Belongs to “Utilities and Others” category after clustering sectors (see Fig. 1).

^c “Other” category here accounts for workplaces measured in the following sectors: mining [median (range) = 249 (28–307) Bq/m³, n = 7], farming [140 (88–191) Bq/m³, n = 2], retail [26 (15–371) Bq/m³, n = 9], health services [118 (24–1860) Bq/m³, n = 39], tourism [83 (13–1521) Bq/m³, n = 48], transport [38 (9–332) Bq/m³, n = 30] and technology [67 (9–602) Bq/m³, n = 52].

^d No exceedances found above 5th floor. Total number of workplaces above 5th floor is 53.

^e Boxplots for visualization of medians and interquartile ranges for each variable and its categories available in supplementary material (Fig. 2S–9S).

levels ranged from 1 to 3226 Bq/m³, with an arithmetic mean of 220 Bq/m³ and a median of 101 Bq/m³. The distribution of radon concentration in the sample can be observed in Fig. 1S. Normality was discarded with Kolmogorov-Smirnov test. Four percent of workplaces (114) exceeded 1000 Bq/m³ and 8% (237) exceeded 600 Bq/m³.

As shown in Table 3, for all binary variables, radon median was significantly different between categories. Median radon concentration was significantly higher in: the public sector vs. private, in workplaces with public permanence vs. without public permanence, in urban vs. rural municipalities, in warm season vs. cold, and in radon prone municipalities vs. not radon prone (see Tables 2 and 3).

For variables work sector and floor, some of their multiple categories had similar radon levels and were combined to create coherent categories for the subsequent multivariate analysis.

Table 3
Bivariate analysis results for each variable.

Variable	Hypothesis test	Sig. value	Hodges-Leman Median difference (95% CI)
Public vs private sector	U Mann-Whitney	<0.001	20 (14–27)
Public permanence	U Mann-Whitney	0.000	30 (23–37)
Urban vs rural	U Mann-Whitney	0.000	19 (12–27)
Season	U Mann-Whitney	<0.001	15 (8–23)
Location radon potential	U Mann-Whitney	0.000	73 (62–87)
Sectors	Kruskal-Wallis	Fig. 1/ 1S	
Floor	Kruskal-Wallis	Fig. 2/ 2S	

3.2.1. Work sector

As shown in Table 2, the percentage of workplaces exceeding 300 Bq/m³ varied between sectors. The highest percentage was found in the Culture and the Education sectors, which registered 28% and 25% of workplaces exceeding 300Bq/m³ respectively. Culture and Education also registered highest levels of radon, with a median of 1.24 and 1.37 Bq/m³ respectively, whereas in the Utilities sector the median radon level was 66 Bq/m³.

The significance of the median difference between sectors is described in Fig. 1. There is no significant difference between Culture, Education and Public Service sectors, and each of them have significantly higher radon median than that found at Utilities, Financial Services, and “Other” sector. Additionally, there is no significant difference between “Other” and Utilities, nor between “Other” and Financial Services,

Following Fig. 1, those work sectors with equivalent radon levels (median difference significance = 1) were combined into one single sector. Thus, the following 4 categories were generated for the multivariate analysis: Education & Culture, Public Service, Financial Services, and Utilities & Others (with former “Other” plus Utilities).

Employers’ self-reported radon levels for underground mines and spas —both sectors are regulated since 2011— are presented in Table 4 (information provided by CSN). Out of the seven currently active

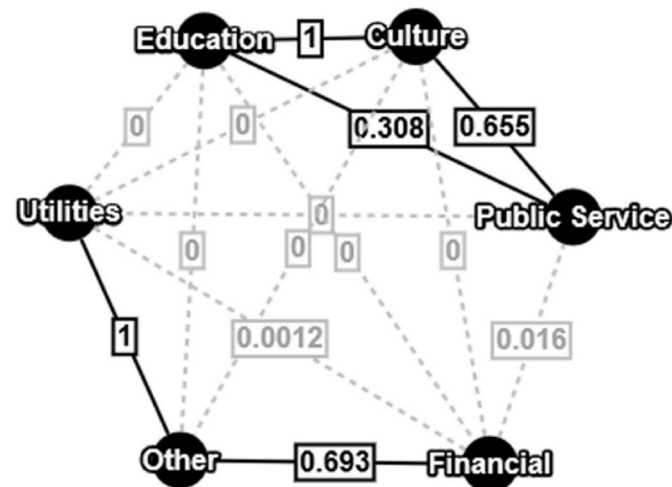


Fig. 1. Graph with median difference significance between sectors. Each vertex represents a sector. Each line shows the significance value (adjusted by Bonferroni correction) for the radon median difference between the connected sectors. Solid lines connect sectors with no significant difference in their radon concentration median (significance >0.05). Dotted lines connect sectors with significantly (<0.05) different radon medians.

Table 4
Radon concentration levels (annual average) in underground mines and thermal spas (AM = arithmetic mean).

Underground Mines	Radon Concentration (Bq/m ³)	
	AM	Max
M1	68	100
M2	34	52
M3	149	280
M4	36	45
M5	188	307
M6	1.820	2.040
M7	32	47
Thermal Spas	Administration/lodging AM (Range*)	Water Treatment AM (Range*)
Radon Prone (N = 5)	109 (34–170)	381 (118–540)
Non Radon Prone (N = 16)	69 (24–210)	309 (67–1.150)

(*) the reported values respectively correspond to the facilities with the minimum and the maximum mean radon concentration, not to individual measurement results.

Source: data provided by the National Safety Council (CSN)

underground mines in the country, only one presents a radon average level above 300 Bq/m³. For spas, out of 47 thermal establishments, less than 20% has radon concentrations exceeding the reference level (mostly associated to patients’ treatment rooms, where worker’s permanence time is low), although very high values (in the order of several thousand Bq/m³) had been detected at 3 facilities. Results in Table 4 correspond to the 21 facilities for which aggregated survey results were available.

3.2.2. Floor

Median radon concentration decreased as floor level increases (Table 2 and visualization in Fig. 8S). There is no significant difference between first, second and above second floor. As shown in Fig. 2, underground floor category has significantly higher median than all the rest of the floors, and ground floor has significantly higher radon median than 2nd floor and above.

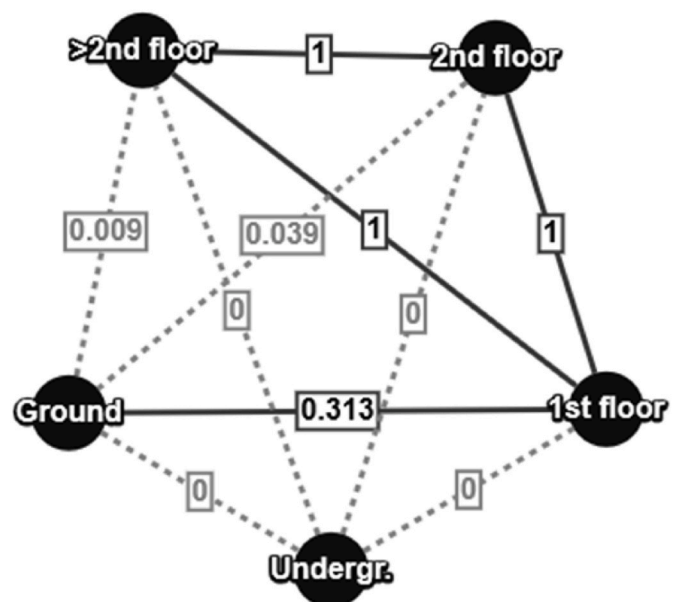


Fig. 2. Graph with median difference significance between floor levels. Each vertex represents a floor level category. Each line shows the significance value for the radon median difference between the connected floors. Solid lines connect floors with no significant difference in their radon concentration median (significance >0.05). Dotted lines connect floor levels with significantly (<0.05) different radon medians.

Thus, this variable was regrouped to have the following 3 significant categories: “underground”, “ground floor”, and “>ground floor” (box-plot available in Fig. 9S).

Of note, we found workplaces exceeding 300 Bq/m³ at all floor levels below 6th floor.

3.3. Multivariate analysis: quantifying indoor radon determinants

3.3.1. Variables selection

The variable Work sector is linked to the ownership type. In our sample we identify two clusters of sectors that closely match with the Public and Private sectors respectively as shown in Table 1S. The Education & Culture sector, with 92% of workplaces of public ownership, and the Public Service sector (100% public), whereas the rest of work sectors are namely of private nature (Financial Services sector is 100% private and “Utilities and Others” sector category is 89% private).

Public permanence variable is linked also to the Work sector variable: 83% of Education & Culture sector workplaces have public permanence, whereas there is no public permanence in 99–100% of workplaces at the Public service, Financial services and “Utilities and Others” sectors. Essentially, public permanence category “yes” mirrors directly the Education & Culture sector. Thus, we kept variable Work sector and excluded the variables Ownership type and Public permanence.

We tentatively included the following variables in the multivariate analysis: work sector, floor, level of urbanization (urban/rural) and season, after confirming the lack of a strong correlation between them (see Table 2S). The highest correlation was found between urban/rural and work sector (0.624). To explore this correlation, we carried a detailed correlation matrix for these two variables (Table 3S). We observed 56% of rural workplaces are from the utilities sector, the sector with lowest levels of radon. On the other hand, 60% of urban workplaces belong to the Education & Culture sector, the sector with highest levels of radon.

The radon potential of the workplace location was included only for adjustment purposes because its distribution is extremely uneven. 95% of our sample is in a radon prone municipality, and only 5% is outside a radon prone municipality, furthermore the latter only has one single measurement exceeding 300 Bq/m³.

3.3.2. Regression models

A linear regression model was obtained using radon concentration as outcome (dependent variable) and Work sector, Floor, Level of Urbanization, Season and Radon potential as independent variables. Variable Season was not significant, but it was kept for adjustment together with radon potential. Sector, Floor and Level of Urbanization were significant in the model (see Table 5). The R2 was 0.072. Compared to first floor, underground and ground floors accounted for 168 and 81 Bq/m³ radon increase respectively. Similarly, compared to financial sector, the

Table 5

Linear regression model results: Radon concentration variation attributed to each variable.

Variable	Category	Ref. category	Radon variation ^a (Bq/m ³)	95% CI	Sig.
Floor	Underground	≥1st floor	168	131–205	<0.001
	Ground floor	≥1st floor	81	56–107	<0.001
Level of Urban.	Urban	Rural	48	10–86	0.014
	Sector				
	Education & Culture	Financial Services	144	105–183	<0.001
	Public service	Financial Services	85	40–130	<0.001
	Utilities & others	Financial Services	–28	(–)78–(+)23	0.281

^a adjusted by season and radon potential of the location.

Education & Culture and the Public Service sectors accounted for 144 and 85 Bq/m³ increase in radon concentration.

A logistic regression model was conducted to obtain Odds Ratios (ORs). We used as outcome variable “radon level >300 Bq/m³” (yes or no); and as independent variables Work sector, Floor, Level of Urbanization. The radon potential and season were included for adjustment. As shown in Table 6, Work sector, Floor, Level of Urbanization yielded significant ORs. Sector and floor reported the highest ORs. For instance, in the Public Service sector the odds of finding radon exceedances were 5.7 times higher than those observed in the Financial Services sector.

4. Discussion

This study comprises over 3000 measurements carried out mostly in radon prone areas of Spain. Overall, 20% of workplaces exceeded the radon reference level of 300 Bq/m³. This percentage of exceedances is, by far, higher than that found in underground mines and spas (see Table 4), commonly regulated sectors at the international level. These results support the European strategy requiring mandatory workplace radon measurements within radon prone areas.

An important take away of the study is that 1 in every 5 workers could be exposed to excessive radon levels in radon prone areas of Spain. For instance, in Galicia, where 70% of the territory is radon prone, by rough estimate, we could expect around 154,000 workers exposed to excessive radon levels. This increases their lung cancer risk, especially for smokers. We also identify that extreme radon levels (<1000 Bq/m³) are not rare; they represent 4% of our sample. Such high radon levels require action, not only as per ICRP recommendations (ICRP, 2014) or European standards, where indoor radon reference levels should be below 300 Bq/m³, but also considering the reference level of 1000 Bq/m³ provided in the IAEA General Safety Requirements Part 3 (IAEA, 2014).

4.1. Floor level and radon potential

Ninety percent of our study sample is located in radon prone areas. Outside radon prone areas, only 1 out of 161 workplaces exceeded the reference level. This is a lower percentage than the one found for residential buildings outside radon prone areas (Ruano-Ravina et al., 2021).

In our sample, we also confirmed that as floor level increases, radon decreases (see Fig. 8S). This trend has been widely confirmed for dwellings in numerous international studies (Sabbarese et al., 2021).

For underground and ground floor, 30% and 21 % of workplaces respectively exceeded 300 Bq/m³. However, for workplaces located on 1st and 2nd floor and higher, 17%–18% still exceeded 300 Bq/m³. Thus, our results indicate that excessive radon levels can be expected, at a significant percentage, in radon prone areas at all floor levels.

EU regulation, Euratom Directive 2013/59, requires mandatory radon measurements at workplaces located on the ground floor or basement level in radon prone areas (article 54). This can be regarded as

Table 6

Logistic regression model results: Odds Ratio (OR) for radon exceedance (>300Bq/m³).

Variable	Category	Ref. category	OR ^a	95% CI	Sig.
Floor	Underground	≥1st floor	2.74	2.07–3.61	<0.001
	Ground floor	≥1st floor	1.37	1.11–1.69	<0.001
Level of Urban.	Urban	Rural	1.45	1.06–1.98	0.02
	Sector				
	Education & Culture	Financial Services	6.55	3.95–10.88	<0.001
	Public service	Financial Services	5.69	3.33–9.73	<0.001
	Utilities & Others	Financial Services	1.31	0.71–2.4	0.384

^a ORs adjusted by season and radon potential of the location.

an effective strategy to prioritize based on radon risk. However, according to our results, workplaces above ground floor level should also be taken into consideration when designing strategies to reduce workers exposure to radon.

4.2. Work sector and urbanization level

The Education & Culture sector, comprising schools, universities, libraries or cultural centers, is, radon-wise, the sector with the poorest air quality. Historically, radon risk was considered exclusively a risk for miners and other specific occupations such as those carried in underground water facilities or spas.

Nevertheless, Spanish data show that workers in radon prone areas in fact receive higher radon doses than underground miners and spa workers. Within radon prone areas, we found that radon levels were excessive in 1 out of 4 workplaces in the Education sector, and over 1 out of 5 in the Public Service sector. These results are in line with an ongoing paradigm change in the way institutions, employers and citizens should consider exposure to radon in the workplace. Radon should no longer be considered a risk for marginal occupations, but a risk everyone has if located in a radon prone area.

Remarkably, educative and cultural institutions have 6.5 times more radon than bank offices (Financial Services sector). Schools and offices have different building structures and ventilation systems, for instance schools do not have air conditioning while most offices do. Also, different occupation habits could lead to different air dynamics. These factors could be behind this difference in radon concentrations. However, these same factors cannot explain the high levels found at the Public Service sector.

The Public Service sector has 5.7 times more radon than the Financial sector. Both are office-like premises, and both usually have forced ventilation. A tentative explanation could be that the public administration often makes use of historic buildings that could have more foundation cracks or poorer insulation from the ground. This could affect radon entry and therefore indoor radon concentration. These potential explanations are also applicable to the Education & Culture sector. In general, we indeed observed the Public sector has higher radon levels than the Private sector.

Rural locations had lower radon levels in our sample than urban ones. Possibly this difference is due its correlation with the working sector variable: 56% of rural workplaces were from the Utilities sector whereas urban workplaces were 60% Education and Culture sector.

4.3. Comparison with previous studies

The present results for radon in workplaces are completely consistent with previous Spanish studies with smaller sample size and coverage (Martín Sánchez et al., 2012; Ruano-Ravina et al., 2019).

Our sample yielded a median radon concentration of 101 Bq/m³, 107 Bq/m³ for radon-prone locations and 28 Bq/m³ outside radon prone locations. This is in line with results found in the UK where the median was 147 and 62 Bq/m³ within and outside radon prone locations respectively (Gooding, 2018). Finland reported a geometric mean of 41 Bq/m³ (Kojo et al., 2023), and Italy and Latvia found a median of 88 Bq/m³ and 48 Bq/m³ (Trevisi et al., 2012; Reste et al., 2022). These variations in occupational radon levels among European surveys are mainly attributed to the geological diversity across regions. Additionally, the presence or absence of underground floors in the surveys could have influence the results: the UK and Italy surveys exclusively examined basements, surveys in Finland and Latvia excluded them, and our study in Spain included all floor levels.

If we look at the Education sector, in contrast to our study, the UK survey found that schools had lower levels of radon than banks and offices (Gooding, 2018); and in Finland schools reported same radon levels as other workplaces (Kojo and Kurttio, 2020; Kojo et al., 2023). On the other hand, in line with our results, in Japan, Latvia and China

studies did report higher levels of radon in schools than in other work sectors (Oikawa et al., 2006; Su et al., 2021; Reste et al., 2022).

4.4. Weaknesses and advantages

Unfortunately, for our dataset information related with building age, construction material or ventilation habits was missing or poorly detailed in some workplaces. These factors could have improved the regression models and bring some better results when it comes to predicting radon levels. Additionally, some variables had asymmetric distributions, for instance some sectors are very well represented such as the Education sector, while others have scarce data and were grouped under “Others”.

There are a number of advantages to this research. The main one is sample size, which ensures a representativeness of several sectors, and other variables. A further advantage is that all measurements have been obtained using the same radon measurement system (alpha-track), which is the most reliable and recommended by national and international organizations. All measurements have been performed by a Galician Radon Laboratory (www.radon.gal), which is certified by the Spanish National Entity of Accreditation for radon measurements.

Finally, we have employed easily understandable variables, enabling a straightforward interpretation of the results.

4.5. Public health implications

Our results, from over 3.000 workplaces in Spain, confirm that immediate action—radon testing and mitigation—is needed to protect workers and the public against radon exposure, especially in radon prone areas. We can confirm that thousands of Spanish workers in radon prone areas have a significant increased risk of lung cancer due to radon exposure. Of particular concern are educational establishments, where not only workers, but also children and adolescents, are exposed to radon concentration significantly higher than for other working sectors. Of note, Spain has the 9th highest prevalence of smokers in Europe (Eurostat, 2022). Radon and tobacco use have a synergistic effect for lung cancer causation, thus actions to avoid smoking initiation and tobacco cessation would immensely contribute to lung cancer risk reduction.

EU regulation on radon will be now enforced in Spain due to its recent national transposition following a 5-year delay. Pertaining competent authorities should execute this regulation without further delay. According to our results, many employers will find excessive radon levels. Employers and workers should be ready to understand the implications of a radon exceedance. Employers must address their responsibility, learn how to follow the new regulation, how to communicate with workers about this risk, and most importantly, how to mitigate radon levels to protect their workers. Remediating excessive radon levels is totally feasible but requires planification and guidance. More evidence is needed to clarify whether employers are indeed understanding and acting upon radon risk. Worker’s representatives should be readily informed about radon risks and make sure employers are acting according to law.

4.6. Conclusions

Some of the main conclusions of our study are applicable on a general basis. Most notably.

- General workplaces (such as offices, schools, and public buildings) in radon prone areas may have radon levels comparable or even higher than those found in other commonly regulated sectors (such as underground mines or thermal establishments). Given the much larger numbers of workers potentially affected, governments need to take this fact into consideration when developing occupational health regulations.

- Within radon prone areas, not only workplaces at basement or ground floor are at risk. A significant percentage of workplaces above the first floor also present indoor radon concentrations above 300 Bq/m³.
- When regulating workers' radon exposure within radon prone areas, ensuring compliance is often challenging. Strategies need to be designed in order to tailor communication campaigns for workers and the public. Inspection efforts are needed to ensure compliance, especially on the most affected sectors such as the Education sector. To this end, studies such as ours are necessary to offer competent authorities a better understanding of prevailing radon levels and their determinants.

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Credit author statements

Lucia Martín-Gisbert: Writing – original draft, Data curation, Formal analysis, Investigation, Funding acquisition, Visualization, Methodology, Cristina Candal-Pedreira: Methodology, Formal analysis, Writing – Review & Edit, Marta García-Talavera San Miguel: Investigation, Resources, Writing – Review & Edit, Mónica Pérez-Ríos: Writing – Review & Edit, Leonor Varela-Lema: Writing – Review & Edit, Juan Barros-Dios: Resources, Alberto Ruano-Ravina: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – Review & Edit. This work is part of the PhD work of Lucía Martín-Gisbert.

On the use of generative AI in scientific writing

During the preparation of this work Lucia Martín-Gisbert used Chat GPT in order to make the title more clear and concise. After using this tool/service, the autor reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

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Alberto Ruano Raviña and Lucia Martín Gisbert are authors of RadonPro, a software tool to control workers' radon exposure. This tool is registered in Spain's Registry for Intellectual Property as property of the University of Santiago de Compostela (license to the University). The full description is available here: <https://pubmed.ncbi.nlm.nih.gov/36141555/>

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envres.2023.117305>.

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