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Review article

Indoor radon concentrations in European kindergartens and other educational facilities

Heidi Salonen [a,b,*], Tunga Salthammer [b,c], Tuomas Alapieti [a], Ati Shirazi [a], Raimo Mikkola [a], Lidia Morawska [b]

[a] Aalto University, Department of Civil and Structural Engineering, PO Box 12100, FI-00076 Espoo, Finland
[b] Queensland University of Technology, International Laboratory for Air Quality and Health, 2 George Street, Brisbane Q 4001, Australia
[c] Fraunhofer WKI, Department of Material Analysis and Indoor Chemistry, 38108 Braunschweig, Germany

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ABSTRACT

Radon and its progeny threaten the health of children, a vulnerable group. However, researchers have focused on children's exposure to radon in residential buildings. This literature review synthesizes existing research to comprehensively examine radon levels in European kindergartens and other educational facilities. We review common measurement methods, collate radon concentrations, identify contributing factors, offer mitigation strategies and recommend systematic strategies for evaluating radon in these environments. Our literature review included 26 search terms employed in combination to identify relevant publications from 2014 to 2024 stored in electronic databases. Exploring relevant reference lists extended the breadth of our source collection, ensuring that we used a wide range of sources to facilitate rigorous analysis. When measured by tracking α radiation activity, radon concentrations vary with the temporal measurement method employed. Our study revealed median radon concentrations between 10 and 1,478 Bq/m^3 with active sampling and between 6 and 360 Bq/m^3 with passive sampling. Notably, 5 % of studies exceeded the European limit of 300 Bq/m^3, while 56 % surpassed the World Health Organizations' (WHO's) recommended limit of 100 Bq/m^3. One concerning finding was that the maximum radon levels in 79 % of the studies exceeded 300 Bq/m^3. Kindergartens displayed higher radon concentrations than schools did. Measures such as regular assessments and harmonised measurement methods are therefore crucial, particularly when energy efficiency measures are involved. We strongly recommend reducing national radon reference values to the WHO- endorsed level of 100 Bq/m^3 and applying consistent radon monitoring and evaluation strategies in all education facilities, particularly those with suspected elevated radon contamination.

1. Introduction

1.1. Background

Radon (^{222}Rn) is a chemically inert, naturally occurring radioactive noble gas. It accumulates in indoor environments where people live, work and learn, if these environments are not adequately ventilated, posing a serious public health risk. The International Agency for Research on Cancer classified radon as a human lung carcinogen in 1988 (World Health Organization, 1988). Radon is the second most common cause of lung cancer after smoking among the general population and the primary cause of lung cancer among those who never smoke (Bulut and Sahin, 2024; Gordon et al., 2018). The emergence of lung cancer in nonsmokers is heavily influenced by radon levels in the surrounding environment and the individuals' duration of exposure to this radon (Heinzl et al., 2024; Sá et al., 2017).

EC Directive 2013/59/Euratom mandates an appropriate level of protection from radon exposure. This directive requires European Union member states to set national reference values for indoor radon concentrations that do not exceed 300 Bq/m^3 and to develop national radon action plans (European Union, 2014). The WHO's radon guidelines, which are based on the "as low as reasonably achievable" (ALARA) principle, recommend a national reference level of 100 Bq/m^3. If this level cannot be achieved, they suggest that the maximum permissible level should not exceed 300 Bq/m^3 (WHO, 2009). In the United States (US), the Environmental Protection Agency's (EPA's) Radon Act 51 sets

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* Corresponding author at: Aalto University, Department of Civil Engineering, PO Box 12100, FI-00076 Espoo, Finland.
E-mail address: heidi.salonen@aalto.fi (H. Salonen).

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the natural outdoor level of radon gas (0.4 pCi/L = 148 Bq/m^3) as the target for indoor radon levels (EPA, 2024). In Finland, indoor radon levels in workplaces are regulated by the Radiation Act, which states that radon concentrations in workspaces with more than 600 h per year of occupancy must not exceed 300 Bq/m^3 (Ministry of Social Affairs and Health, 2018). Many other countries have similarly established reference levels, guidelines and limit values for radon, which typically range from 100 Bq/m^3 to 400 Bq/m^3, but these levels are often defined with reference to different exposure times (Dimitroulopoulou et al., 2023).

Even low concentrations of radon can increase the risk of lung cancer, particularly in susceptible individuals, such as children (Bochicchio et al., 2014). Indeed, there is no known threshold below which radon exposure does not present a risk (Branco et al., 2016). Lorenzo-González et al. (2019) found that radon is a clear risk factor for lung cancer in never-smokers, with significant risk observed in individuals exposed to radon levels above 200 Bq/m^3.

The danger to children attending kindergartens and other educational facilities with high radon levels is particularly concerning, as they may be exposed for prolonged durations over many years during a biologically vulnerable period of their lives (Gordon et al., 2018). However, the issue of radon exposure in these settings has received much less attention than studies on homes, resulting in scarce and scattered information. Additionally, to correctly interpret measurement data, there is a need for detailed information on the sampling method, sampling duration and detection of α radiation (Mphaga et al., 2024).

1.2. Scope and aims of the study

Although considerable research has investigated radon risks in residential areas, there remains a significant gap in literature reviews specifically targeting educational facilities. This review aims to address this gap by focusing on radon exposure risks in kindergartens and schools. In a background search of previously published review articles, we found only one paper that examined radon concentrations in such buildings (Zhukovsky et al., 2018). Although studies of radon levels in European schools and kindergartens were included in that study, the perspective of the article was global, and the reasoning behind the results was somewhat inadequate. In contrast to Zhukovsky et al.'s (2018) broadly scoped review, which provided insufficient coverage of measurement techniques and mitigation strategies specific to European educational facilities, our study addresses these precise deficiencies. By focusing on measurement methods and influencing factors unique to kindergartens and schools, we aim to provide a detailed understanding that fills these critical gaps.

Given that children in educational facilities face a dangerous risk of exposure, our study seeks to pioneer research stream on this topic. With such challenges and critical caps in mind, the present study attempts to fill these knowledge gaps by conducting a comprehensive literature review. We adopted five central objectives:

1. *Identify the most common methods for measuring radon.* We sought to understand the applicability and significance of these methods while identifying their comparative advantages and ideal areas of use
2. *Summarise radon concentrations in European kindergartens and other educational facilities.* Drawing from a diverse array of relevant European studies, we aimed to present an overview of radon concentrations in these settings. This was designed to reveal the scope and severity of the existing problem
3. *Examine the factors contributing to variability in indoor radon levels in educational facilities.* This involves a detailed investigation of the different spatial concentrations, building construction, material composition, ventilation practices, and environmental conditions affecting radon concentrations in these settings. By targeting specific aspects such as room location (e.g., basement versus upper floors), building materials (e.g., radon-emitting construction materials), and seasonal variations (e.g., changes in radon levels across different weather conditions), we aim to identify key determinants of radon concentrations in kindergartens and schools
4. *Provide recommendations for mitigating radon levels.* Beyond merely identifying the issue, this study strove to propose mitigation strategies and tangible recommendations for reducing radon levels in these settings
5. *Present strategies for evaluating radon concentrations.* Finally, to facilitate continuous monitoring and control, we offer a harmonised approach to measuring and evaluating radon levels – Particularly in facilities suspected of high radon concentrations or requiring routine checks

The potential health implications of radon exposure weave together the education, public health and environmental conservation sectors, necessitating an inclusive, evidence-based approach. By fulfilling these objectives, this study contributes to the ongoing body of knowledge on radon. We hope to inspire the creation of improved guidelines, support the development of balanced policies and encourage practices that facilitate a safer environment for children's education across Europe and beyond. Our goal is not only to fill the existing knowledge gap but also to catalyse a broader discussion of children's health and safety in their learning environments.

2. Material and methods

2.1. Planning and scoping

To establish a background for the study, we searched for existing review articles related to radon exposure in educational facilities. Specifically, we searched for relevant literature in review-specific databases (Epistemonikos, Cochrane Database of Systematic Reviews, Inplasy, Prospero) and open platforms (Zenodo, and OSF), as well as more general databases of scientific literature (PubMed and Web of Science; see Table S1 "Summary of searches for previously published review articles between January 2014 and January 2024" in the Supplementary Material. Reviews closely related to our topic were first examined to avoid overlapping and duplicated studies and ensure the originality of our work. We included articles published between January 1, 2014, and December 31, 2024. To gain a broad perspective on the published literature, the searches began with the search term 'radon'. We targeted titles and abstracts from all fields when the selection of titles and abstracts specifically was not possible. If the initial search returned over 80 articles, the search was continued with the search terms 'radon' AND 'indoor', and 'radon' AND 'indoor' AND 'schools' OR 'kindergartens' OR 'nurseries' OR 'university buildings' OR 'educational buildings'. If the database did not allow direct searches of review articles, the search term AND 'review' was used. Additionally, if the initial search returned less than 80 articles, the search was continued in a similar manner to ensure that all relevant publications were assessed.

The search resulted in 289 publications. After further assessment (removing irrelevant papers based on titles and abstracts, removing duplicates) eight review articles were selected for more detailed review of the full articles. Finally, seven review articles were identified as relevant publications, and their summaries are included in Table S2 in the Supplementary Material. A comparison of these studies with ours is made in section 3.8. Our scoping exercise revealed that previous reviews predominantly focus on residential settings, lacking detailed analysis of non-residential environments, including kindergartens. By examining gaps like inconsistent mitigation strategies and insufficient geographic coverage, we formulate precise research questions designed to address these unmet needs.

2.2. Search strategy

We then moved on to our primary search. For this step, in November and December 2024, we searched for literature in Scopus, PubMed and

Google Scholar. Material published between January 1, 2014, and December 31, 2024, was included, but key older studies were considered when necessary. Additionally, we consulted ISO Series 11665 to identify radon measurement methods. The search terms used in the Google Scholar and PubMed literature searches, which targeted titles and abstracts, included ‘radon’ AND ‘indoor’ AND ‘exposure at schools’ OR ‘exposure in kindergartens’ OR’ OR ‘“exposure at university buildings’ OR ‘ exposure in educational buildings’ OR ‘concentration OR concentrations at schools’ OR ‘concentration OR concentrations in kindergartens’ OR ‘concentration OR concentrations in nurseries’ OR ‘concentration OR concentrations at university buildings’ OR ‘concentration OR concentrations in educational buildings’ OR ‘track detector’ OR ‘electret’ OR ‘active sampling’ OR ‘passive sampling’ OR ‘scintillation’ OR ‘γ-spectrometry’ OR ‘Lucas cell’ OR ‘ionization’ OR ‘semiconductor’.

To ensure we covered as broad a portion of the published literature as possible, we conducted a secondary search using search strings tailored to each database. The details of this secondary search are presented in Table S3 in the Supplementary Material.

2.3. Eligibility and screening

The primary search resulted in 271 publications. After removing 36 duplicates, we reviewed the abstracts of the remaining 235 publications. After we excluded 134 irrelevant abstracts – either the topic was not relevant, or the article discussed only a case study outside Europe – 101 publications were assessed for eligibility. Eligible material included full-text articles that were written in English or German and freely available or downloadable through the library services of Aalto University (Aalto) or Queensland University of Technology (QUT). In total, five full-text articles were excluded: two were not available in English or German, and three were not freely available or downloadable through Aalto or QUT. The search was then extended to the reference lists of the 96 selected publications. Based on the titles, we screened the abstracts of a further 43 publications. The final selection from this latter pool was made based on a full-text screening. In total, we identified 117 (96 + 21) relevant, peer-reviewed scientific journal articles, literature reviews, books, book chapters, conference articles (full papers) and reports that fulfilled our criteria. These 117 works were included in the final qualitative data synthesis. Of these publications, 62 were selected for quantitative review. In addition, the secondary search (Table S3) resulted in 8 relevant publications, which were also included in the review. These 70 (62 + 8) studies reported indoor radon concentration measurements in kindergartens and/or educational facilities and described the measurement methods employed.

One researcher conducted the initial literature search for radon data, while three researchers screened all studies related to radon in kindergartens and other educational facilities included in both qualitative and quantitative synthesis. Two reviewers independently screened abstracts and full texts, reaching consensus on their conclusions. The average

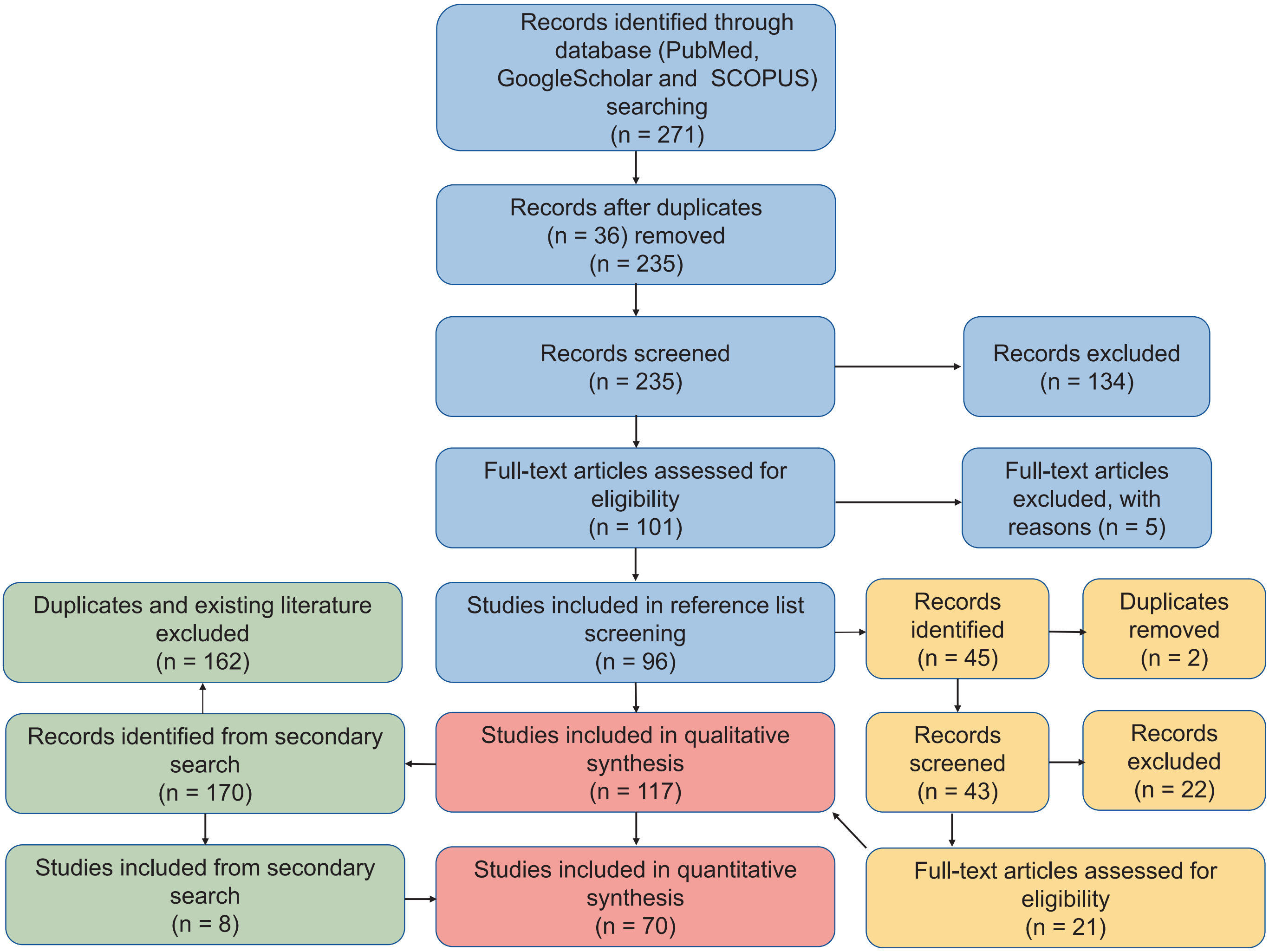

Fig. 1. Flowchart describing the literature search and selection process. Blue indicates searches for articles in databases. Yellow denotes searches of article reference lists. Green displays the secondary search of articles. Red identifies the numbers of articles ultimately selected for qualitative and quantitative synthesis.

disagreement rate was less than 5 % (3 out of 65), with all disagreements resolved by consensus. Two researchers were responsible for the search and analysis of review-specific databases (Epistemonikos, Cochrane Database of Systematic Reviews, Inplasy, Prospero) and open-access platforms (Zenodo and OSF), as well as general scientific literature databases (PubMed and Web of Science). The disagreement rate in this process was 0 %.

The literature search and selection process are visualised in Fig. 1, and detailed inclusion and exclusion criteria are presented in Table S4 in the Supplementary Material.

2.4. Data extraction and analysis; statistical metrics

The following information was collected from the publications that reported radon concentrations in kindergartens and other educational facilities: the types of buildings, number of buildings and number of rooms included; the country and city or area studied; sampling method (active or passive) and measurement technique; the measurement time and temporal resolution, period (date) of measurement, the radon concentrations (median, geometric mean, geometric standard deviation, minimum–maximum values and other statistics if reported; and the main findings and conclusions. In further analyses, studies were classified as either kindergarten studies or other educational building studies (with the latter including schools, universities and preuniversity educational facilities).

We employed various statistical metrics to analyse data on radon concentrations in European kindergartens and other educational buildings. To select these metrics, we drew on conventions and methodologies established in previous research in health and environmental studies. The metrics chosen and the rationales for their use are as follows (Ott, 1995):

- The *arithmetic mean* is the sum of all values in the data set divided by the number of all values and is the central measure of normally distributed data. This metric is sensitive to outliers and does not represent the central value in skewed distributions.
- The *geometric mean* is the *n*th root of the product of all values in the dataset. This measure is particularly suitable for data that are log-normally distributed. It is less affected by extreme values and can be used to gain insights into the typical pattern of radon concentration levels. Note that the geometric mean is always smaller than the arithmetic mean.
- The *median* represents the middle value in a numerically sorted data set. It is useful for providing a robust measure of the central tendency in distributions with skewness or outliers. This measure was chosen to accurately depict the central positions of radon concentrations, especially when the data exhibited non-normal distributions.

These parameters are common for statistical data analysis in environmental research. This ensures that our study adheres to the terminology and methodology of referenced radon concentrations. We are aware that the arithmetic mean is not a reliable measure for the non-symmetrically distributed radon data. Therefore, this parameter was used only when unavoidable, for example, when no other statistical values were provided in cited publications (Heinzl et al., 2024).

2.5. Evidence synthesis

We used both qualitative and quantitative approaches to synthesise the collected data. The qualitative approaches included collecting information about radon measurements, the physical properties of the radon, factors that influenced radon concentrations in kindergartens and other educational facilities and radon regulations and mitigation strategies in kindergartens and other educational facilities, and methods of reducing radon exposure in these buildings. The quantitative synthesis was conducted by collating radon concentration data from the selected studies. These data were then visually represented using box-whisker plots, providing a visual summary of the reported median and geometric mean radon concentrations.

A narrative synthesis approach was adopted to further analyse our findings. This entailed summarising the evidence in a descriptive format. This also enabled us to develop a detailed radon measurement and evaluation protocol. Visualised in Fig. 6, this protocol outlines a strategy for assessing radon in kindergartens and other educational facilities with suspected high radon levels or those requiring routine monitoring. This holistic approach – combing quantitative and qualitative approaches – enables a comprehensive explication of our findings.

3. Results and discussion

3.1. Physical properties of radon

Radon is a colourless and odourless radioactive noble gas denoted by the element symbol Rn and the atomic number 86. A total of 39 isotopes from ^{193}Rn to ^{231}Rn have been detected, as have some nuclear isomers. All isotopes are radioactive, and six isotopes occur in natural radioactive decay chains (Wang et al., 2021). The most stable isotope is ^{222}Rn, an intermediate product of the ^{238}U decay chain with a half-life of $t_{1/2} = 3.8235$ days. This is usually the isotope specified in discussions of indoor radon. ^{222}Rn decays through α radiation into ^{218}Po. Some other short-lived progenies of ^{222}Rn down to ^{210}Pb ($t_{1/2} = 22.3$ years) are listed in Equation (1). The stable isotope of the ^{238}U chain is ^{206}Pb.

$$^{222}Rn \xrightarrow{\alpha(3.82\ d)} {}^{218}Po \xrightarrow{\alpha(3.10\ min)} {}^{214}Pb \xrightarrow{\beta^-(26.8\ min)} {}^{214}Bi \xrightarrow{\beta^-(19.7\ min)} {}^{214}Po \xrightarrow{\alpha(164\ \mu s)} {}^{210}Pb \qquad (1)$$

The second most common isotope is ^{220}Rn (thoron), an intermediate of the ^{232}Th decay chain with a half-life of $t_{1/2} = 55.60$ s. The third isotope with some significance for the environment is ^{219}Rn, an intermediate of the decay chain of ^{235}U with a half-life of $t_{1/2} = 3.96$ s (Baskaran, 2016).

As a noble gas, radon does not react under environmental conditions. The polarizability of the closed-shell radon atom is higher than that of the noble gases with lower atomic numbers. However, with a value of $4.83 \bullet 10^{-24}$ cm^3 (Rumble et al., 2021), it is still small. This produces weak van der Waals forces and, consequently, weak interactions with other molecules and surfaces. The vapor pressure reaches atmospheric pressure at 211.4 K and is approximately $1.1 \bullet 10^3$ kPa at 298 K. This value was estimated from graphically displayed data published by Ferreira and Lobo (2007). Nevertheless, to explain its entry into indoor spaces, it is important to understand how radon is distributed between the relevant environmental compartment's air and water, on the one hand, and its air and organic material, on the other hand. The air/water partitioning is determined by the Ostwald coefficient, the Henry constant and the mole fraction. Using the data given in Table 1, a solubility of $9.3 \bullet 10^{-3}$ mol/L at 298 K can be calculated, which corresponds to 2.1 g/L. An equation given by Schubert et al. (2012) yields a K_{AW} value of 4.54 at 298 K (note that in the literature, the inverse value, water/air, is often used). For an octanol/water system, Wong et al. (1992) report a K_{OW} value of 32.4 at 293 K. Diffusion is another parameter that determines the dynamics of radon in soil air, groundwater, outdoor air and indoor air. For air and water, the values can be calculated with very high accuracy (see Table 1); for solid material, the diffusion depends on porosity, cavity and cracks (Appleton, 2013; Nazaroff, 1992). The density of radon is 9.73 kg/m^3 (273 K, 101325 Pa), which is significantly higher than that of air.

The data presented in Table 1 show that radon atoms do not interact with surfaces or airborne aerosols indoors but rather accumulate in the gas phase. According to Wang et al. (2025), activated carbon represents an effective radon sink, while the effect of other materials can be neglected. The water solubility of radon is low. Deposition rates and gas/particle partition coefficients are largely related to radon progeny

Table 1
Physical properties of the ^{222}Rn isotope.

Parameter	Value	Reference
Isotope	^{222}Radon	
Chemical symbol	^{222}Rn	
CAS number	10043–92-2	
Atomic number	86	
Mass	222.02 g/mol	
Density (273 K, 101325 Pa)	9.73 kg/m^3	(Baskaran, 2016)
Boiling point (101325 Pa)	−61.8 °C	(Baskaran, 2016)
Vapor pressure (298 K) (estimated)	≈1.1 10^3 kPa	(Ferreira and Lobo, 2007)
Ostwald coefficient (298 K)	0.2263	(Clever,1979)
Solubility in water (mole fraction, 298 K)	$1.671•10^{-4}$	(Clever,1979)
Henry's law constant (298 K)	$9.4•10^{-5}$ mol/(m^3 Pa)	(Sander, 2023)
K_{AW} (298 K)	4.54	(Schubert et al., 2012)
K_{OW} (293 K)	32.4	(Wong et al., 1992)
Diffusion coefficient in air[a]	$1•10^{-5}$ m^2/s	(Baskaran, 2016)
Diffusion coefficient in water[a]	$1•10^{-9}$ m^2/s	(Baskaran, 2016)
Radioactive decay	α	(Baskaran, 2016)
Decay chain	Uranium-238	(Baskaran, 2016)
Decay energy	5.49 MeV	(Baskaran, 2016)
Half-life, $t_{1/2}$	3.8235 days	(Baskaran, 2016)
Decay constant, k_D	$2.098•10^{-6}$ s^{-1}	(Baskaran, 2016)

[a] Approximate values, no temperature specified.

(Vaupotič, 2024), but a detailed discussion of this topic is beyond the scope of our review. The diffusion coefficient in air is on the order of that of nitrogen and other small molecules (Schwarzenbach et al., 2017), so the dynamics of radon are determined by air movement.

3.2. Radon measurement

Radioactive decay is determined purely stochastically and independent of environmental conditions. Therefore, it is only possible to predict the probability with which the atom will decay within a certain period. This probability can be determined using the strictly mono exponential decay rate k_D, the mean lifetime $\tau = 1/k_D$ and the half-life $t_{1/2} = \ln 2•\tau$. For ^{222}Rn, $t_{1/2} = 3.8235$ days means that after this time the atom has decayed with a probability $p = 0.5$, while $p = 0.75$ after $2•t_{1/2}$, $p = 0.875$ after $3•t_{1/2}$ and so on. The unit for counting radioactive decay levels per second is the Becquerel (Bq), which is expressed in relation to 1 m^3 of air volume for radon. The old unit was the Curie (Ci), the conversion factor is 1 Ci = $3.7•10^{10}$ Bq.

The statistical nature of radioactive decay generates a priori a statistical error in the measurement that cannot be avoided. The exact statistical description of radioactive decay is given by the binomial distribution. Under certain conditions – that is, with a very large number of atoms and a short observation time compared to the half-life – the binomial distribution can be approximated by the discrete Poisson distribution (Bevington and Robinson, 2003). If, for example, a radon decay rate of $\mu = 50$ Bq/m^3 is measured in a room, the probability that exactly k decay events will occur within one second is given by Equation (2). Another advantage of the Poisson process is that the square root of μ provides the standard deviation of the distribution with $\sigma = \sqrt{\mu}$. Fig. 2 shows the Poisson distributions for radon air concentrations of $\mu = 10$ Bq/m^3 and $\mu = 50$ Bq/m^3. Note that the Poisson distribution is asymmetric for small k values and approaches a Gaussian distribution with increasing k.

$$\boldsymbol{P_\mu(k)} = \frac{\boldsymbol{\mu^k}}{\boldsymbol{k!}} \cdot \boldsymbol{e^{-\mu}} \tag{2}$$

A detailed understanding of the statistics of radioactive decay is crucial for conducting accurate radon measurements. As shown in Equation (1), ^{222}Rn is followed by four short-lived radon daughters – two of which are α emitters – with a total average lifetime of 71.6 min (Baskaran, 2016). This fact must be statistically considered when calibrating measuring instruments and evaluating signals.

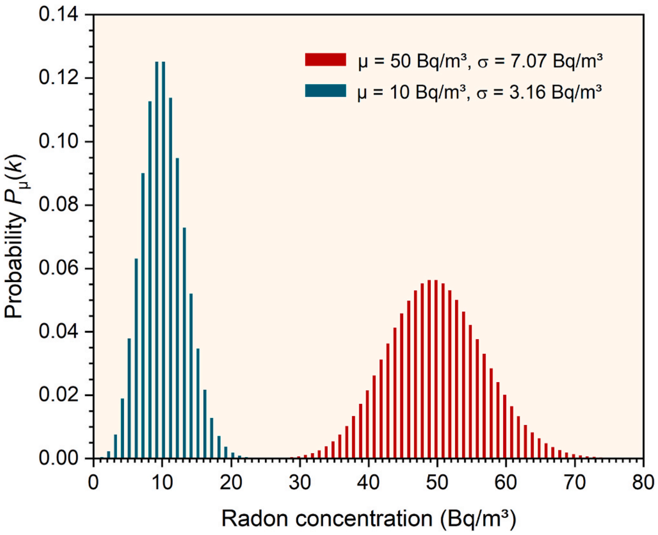

Fig. 2. Poisson distributions $P_\mu(k)$ of radon concentrations in air with $\mu = 10$ Bq/m^3 (green) and $\mu = 50$ Bq/m^3 (red).

Various methods are available for measuring radon in indoor air, but their uses fundamentally differ. First, it must be clear whether the measurement is targeted at radon or at radon and other radioactive emitters. Mid- and long-term exposure is determined by passive sampling, while active methods are suitable for measuring short-term exposure. Heinzl et al. (2024) pointed out that a 1-year measurement exhibits greater statistical variability than a 30-year measurement. Therefore, mid- and short-term data must be corrected to determine long-term exposure, which leads to a reduction of extreme values and outliers. Consequently, the correction has a large influence on the arithmetic mean and 95th percentile, but only a small influence on the median and geometric mean.

A signal analysis can be performed directly by detecting the α radiation or indirectly by measuring the γ-radiation of ^{214}Pb and ^{214}Bi. Depending on the type and implementation of the measurement, several sources of error must be considered that have nothing to do with the statistical nature of radioactive decay. These errors concern the dynamics of the radon atoms, which are determined by the air flow, room climate, diffusion effects (Underhill, 1993) and performance of the measurement devices (Rey et al., 2024).

The most common passive measurement methods employ a track detector or an electret. A track detector consists of a special polymer film in a diffusion chamber. A diffusion membrane ensures that only radon atoms from the ambient air – and not radon decay products – enter the chamber. The α particles released by radon and radon progeny within the diffusion chamber leave tracks when they hit the detector film. After the measurement is complete, the tracks are enlarged using chemical agents and then counted. The exact exposure time of the detector must be known. The ^{222}Rn activity is then calculated using a calibration function based on regression models. The electret contains an electrically charged detector disc whose voltage decreases with each radioactive decay event in the diffusion chamber. At the end of the measurement period, the voltage drop is measured. It can be helpful to determine the baseline of the passive detector in parallel to the actual measurement by storing devices of the same type in a room with low ^{222}Rn activity.

Active radon measurements are usually carried out to determine the actual radon concentration in a room or other specific location and how this concentration changes over a certain period. The Lucas cell is widely used and is suitable for both grab sampling and continuous monitoring (Abbady et al., 2004). Radon is pumped into the cell from the ambient air so that the products of radon decay are retained. An electronic detector in the cell records the emitted radiation. Various physical effects can be used to facilitate this measurement. In ionisation chambers, the radiation releases electrons due to the photoelectric effect, which the detector amplifies and registers. In semiconductor materials radioactive radiation creates free electrons that are deflected by an electric field and registered by detectors. With the scintillation method, radioactive radiation stimulates certain materials to emit light. The detector amplifies and registers these light signals. The Lucas cell is often operated in combination with scintillation. ^{222}Rn in air can also be determined by measuring ^{214}Pb and ^{214}Bi using γ-spectrometry. Sorption on filters is commonly employed to sample radon progeny (Baskaran, 2016). This technique can be designed to mimic the deposition process in the respiratory tract (Papenfuß et al., 2023).

Common active and passive methods for sampling and measuring radon are shown in Fig. 3. Methods for measuring radon in air are standardised by the ISO 11665 series. A summary of the standards relevant to indoor environments is shown in Table 2. A very good general overview of the detection and measurement of radioactive radiation is provided by Knoll (2010). The pros and cons of short-, mid- and long-term radon measurement have been discussed by Tsapalov and Kovler (2022) and Mphaga et al. (2024). Despite this variety of standards, the quality of radon measurements is often difficult to assess. Only those active and passive devices that allow the results to be traced back to a primary standard should be used. This is usually part of a validation process (Wiedner and Rupp, 2023).

Table 2
Standards of the ISO 11665 series relevant to the measurement of radon in indoor air.

Method	Standard/ Reference
Origins of radon and its short-lived decay products and associated measurement methods	(ISO 11665-1, 2019)
Integrated measurement method for determining average potential alpha energy concentration of its short-lived decay products	(ISO 11665-2, 2019)
Integrated measurement method for determining average potential alpha energy concentration of its short-lived decay products	(ISO 11665-3, 2020)
Integrated measurement method for determining average activity concentration using passive sampling and delayed analysis	(ISO 11665-4, 2021)
Continuous measurement methods of the activity concentration	(ISO 11665-5, 2020)
Spot measurement methods of the activity concentration	(ISO 11665-6, 2020)

3.3. *Radon concentrations in European kindergartens and other educational facilities*

Alter and Oswald (1983) first proposed using log-normal distribution to conduct indoor radon measurements. Ott (1990) later provided a physical explanation for why log-normality generally applies to the distribution of air pollutants. However, Daraktchieva et al. (2014) identified systematic deviations from the log-normal distribution in some datasets, which could not be attributed to statistical uncertainties. Therefore, we have refrained from specifying arithmetic means, which assume a normal distribution. Instead, we use the 50th percentile (median), other percentiles and ranges to present our data. Many studies provide only geometric means. Accordingly, we used this parameter, but we were unable to verify its quality – for instance, regarding the correction of outliers – in most cases.

We identified 70 original studies that examined a total of 18,098 European facilities. Of these, 28 were university buildings, 507 were preuniversity educational buildings, 2,851 were schools, 1,183 were kindergartens, 2 were nurseries and 13,548 included both school buildings and kindergartens/nurseries. These studies all reported indoor radon concentrations. A statistical summary of these studies is provided in Table 3. The detailed measurement and analysis methods employed in these studies, along with the main findings and conclusions, are presented in Tables S5 and S6, respectively, in the Supplementary Material. Having reviewed Martin-Gisbert et al. (2023), we noted their inclusion of sports facilities under 'Educational buildings.' As we did not consider sports facilities within this category and could not reliably distinguish data among the different building types, we decided not to include their data in our review. Additionally, publications where data from educational buildings could not be distinguished from data for other types of

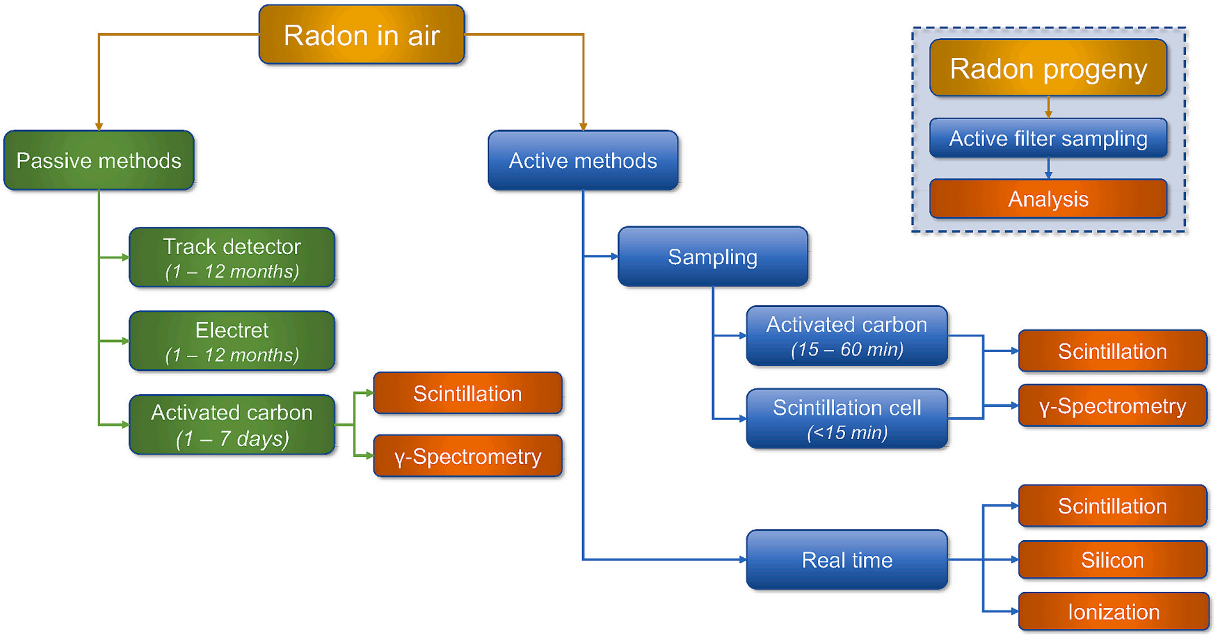

Fig. 3. A Selection of common active and passive methods for measuring concentrations of ^{222}Rn in air. The sampling times indicate typical values. Since radon progeny are metals, sampling is carried out actively on filters, and the usual techniques can be applied for detection.

Table 3
Statistical breakdown of indoor radon concentrations (Bq/m^3) in kindergartens and other educational facilities in various European countries.

Number of buildings (number of rooms) *[Type of buildings]* City/area, Country	Reference	Sampling method (active/ passive) *Sampling time*	Indoor radon concentrations (Med, GM, GSD, Min-Max + other statistics if reported)
1 (29) *[University building; offices (n = 18), classrooms, canteen, and toilets]* Buca district of Izmir, Turkey	(Alkan and Karadeniz, 2014)	Track detector (passive) *~ 1 month (two periods)*	1st period Med: 161; GM: 152; GSD: NR; Min-Max: 62.5 ± 5–335 ± 13 2nd period: Med:135; GM: 111; GSD: NR; Min-Max: 77 ± 5–328 ± 14
50 (602) *[Kindergartens]* Montana, Bulgaria	(Angelova et al., 2023)	Track detector (passive) *4 months*	Med: 84; GM: 88; GSD: 2.23; Min-Max: 10–1439
2 (2) *[Kindergartens]* Banja Luka, Republic of Srpska	(Antunovic et al., 2023)	Continuous radon monitor (active) *1 week*	Med: NR; GM: NR; GSD: NR; Min-Max: 38.9 ± 12–312 ± 31
5(5) *[University buildings]* Bolu, Turkey	(Atik et al., 2016)	Continuous radon monitor (active) *1 year*	Med: 17; GM: NR; GSD: NR; Min-Max: 0–85
19 (28) *[Schools]* Nuoro, Italy	(Azara et al., 2018)	Continuous radon monitor (active) *72 h*	Med: 91.6 (45.0–140.3); GM: NR; GSD: NR; Min-Max: NR-1147
1 (4) *[University building]* Vilnius, Lithuania	(Baltrėnas et al., 2020)	Continuous radon monitor (active) *8 months*	Med: NR; GM: NR; GSD: NR; Min-Max (mean values): 25.6–47.9
115 (NR) *[Schools]* *23 European* countries, 54 Cities	(Baloch et al., 2020)	Track detector (passive) *4 weeks*	Med: 113.8; GM: NR; GSD: NR; Min-Max: NR; P10: 30; P99: 3785
109 (109) *[Schools and kindergartens]* Alba, Bacau, Cluj, Satu-Mare, and Sibiu, Romania	(Bican-Brisan et al., 2022)	Track detector (passive) *3 months*	Alba (n = 20): Med: 360; GM: 313; GSD: NR; Min-Max: 23–1121 (all locations) Bacau (n = 15): Med: 116; GM: 103; GSD: NR Cluj (n = 34): Med: 97; GM: 99; GSD: NR Satu-Mare (n = 15): Med: 125; GM: 125; GSD: NR Sibiu (n = 25): Med: 69; GM: 60; GSD: NR
327 (639) *[Schools]* Southern Serbia	(Bochicchio et al., 2014)	Track detector (passive) *Two 6-month periods or one 12-month period*	Med: 97; GM: 100; GSD: 1.8; Min-Max: 17–607
NR (416) *[Kindergartens, nurseries, and schools]* Galicia, Spain and the Norte de Portugal Region, Portugal	(Branco et al., 2023)	Track detector (passive) and Continuous radon monitor (active) *>3 months (passive), >2 days (active)*	Med: 181; GM: 185; GSD: NR; Min-Max: 3–3039*
15 (47) *[Schools and nurseries]* Porto and Bragança, Portugal	(Branco et al., 2016)	Continuous radon monitor (active) *From 24 h up to 9 days*	Med: ~10-~150; GM: NR; GSD: NR; Min-Max:0–888
9 (38) *[University buildings]* Giresun, Türkiye	(Büyükuslu et al., 2018)	Track detector (passive) *3 months*	Med: 186; GM: 179.4; GSD: NR; Min-Max:76–504
91 (NR) *[Kindergartens]* Plovdiv, Bulgaria	(Cenova et al., 2017b)	Track detector (passive) *3 months*	Med: 275; GM: 230; GSD: NR; Min-Max: 54–1094
6 (18) *[Schools and a nursery]* London, UK	(Chatzidiakou et al., 2015)	Track detector (passive) *1 month*	Med: NR; GM; NR; GSD: NR; Min-Max: 0–~150 (building averages)
130 (1490 premises) *[Kindergartens]* Vratsa, Lovech, and Montana districts, Bulgaria	(Chobanova et al., 2023)	Track detector (passive) *4 months*	Med: 109; GM: 119; GSD: NR; Min-Max: 10–2029
In 2013–2014: 29 (NR) In 2021; 49 (NR) *[Schools and kindergartens]* 2013–2014 study: Ungheni, Causeni, Leova, Criuleni, Ialoveni, Hancesti, and Comrat; 2021 study: Chisinau municipality, Republic of Moldova	(Coretchi et al., 2023)	Continuous radon monitor (active) *3–4 h (2013–2014), 20 days (2021)*	2013–2014 study (schools and kindergartens): Med: 59; GM: 105.2; GSD: 2.27; Min-Max: 26–607 2021 study (schools and kindergartens): Med: 96; GM: 86; GSD: 2.94; Min-Max: 231.8–1129.3 (schools); 17.4–657.9 (kindergartens)
88 (195) *[Kindergartens]* Hungary	(Csordás et al., 2021)	Track detector (passive) *3-month measurement for each season (total four measurements)*	Med: 52; GM: 52; GSD: NR; Min-Max: 14–160
1(13) *[School]* North region of Portugal	(Curado et al., 2020)	Continuous radon monitor (active) *1 month*	Med: ~120–~500; GM: NR; GSD: NR; Min-Max: 0–~1400
25 (44) *[Schools]* Banja Luka, Republic Srpska	(Ćurguz et al., 2015)	Radon: Track detector (passive) Progeny: Direct radon-thoron progeny sensors (DRPS-DTPS) (passive) *Radon: 12 months, Progeny: 6 months*	Med: 82; GM: 99; GSD: 1.94; Min-Max: 36–549 Equilibrium equivalent radon (EERC) (n = 25): Med: 11.5; GM: 1.26; GSD: 2.20; Min-Max: 6.8–16.8
50 (141) *[Schools]* 15 municipalities, Republic of Srpska	(Curguz et al., 2020)	Track detector (passive) *~1 year*	Ground floor (n = 100): Med: 210; GM: NR; GSD: NR; Min-Max: 89–4244 1st floor (n = 41):

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Table 3 (*continued*)

Number of buildings (number of rooms) *[Type of buildings]* City/area, Country	Reference	Sampling method (active/ passive) *Sampling time*	Indoor radon concentrations (Med, GM, GSD, Min-Max + other statistics if reported)
			Med: 150; GM: NR; GSD: NR; Min-Max: 75–655
42 (126) *[Schools]* Batman, southeastern Anatolia, Turkey	(Damla and Aldemir, 2014)	Track detector (passive) *3 months*	Med: 42; GM: 42; GSD: 1.7; Min-Max: 14–307
157 (411) *[Kindergartens]* Razgrad and Silistra, Bulgaria	(Djounova et al., 2023)	Track detector (passive) *~3 months*	Med: 108; GM: 108; GSD: 2.19; Min-Max: 10–1087
41 (343) *[Schools, kindergartens, and a nursery]* Cluj and Constanta, Romania	(Dobrei et al., 2024)	Track detector (passive) and Continuous radon monitor (active) *NR (passive), ~7 days (active)*	Passive (n = 343): Med: 168; GM: 172; GSD: 2.4; Min-Max: 14–1495 Active (n = 134): Med: 317; GM: 308; GSD: 1.9; Min-Max: 43–1556
10,087 (35500) (measured in the early 1990 s) 679 (NR) (measured in 2011–2012) 540 (NR) (measured in 2012–2013) *[Schools and Kindergartens]* Czech Republic	(Fojtíková and Rovenská, 2014)	In 1990 s and 2011–2012: Track detector (passive) and in 2012–2013: Continuous radon monitor (active) *1 year (1990 s), ~10 months (2011–2012), and > 7 days (2012–2013)*	1990 s: Med: NR; GM: 124; GSD: NR; Min-Max: 0– >1600 2011–2012: Med: NR; GM: NR; GSD: NR; Min-Max: NR 2012–2013: Med: NR; GM: NR; GSD: NR; Min-Max: NR
3 (3) *[Schools]* Cassino, Italy	(Fuoco et al., 2015)	Continuous radon monitor (active) *5 days*	Med: NR; GM: NR; GSD: NR; Min-Max: 21–174*
3 (4) *[A school and kindergarten]* Telemark, Norway	(Haanes et al., 2019)	Track detector (passive) *133 days (non-heating season) 112 days (heating season)*	Med: NR; GM: NR; GSD: NR; Min-Max: NR–860 (non-heating), NR–290 (heating)
230 (2427) *[Schools]* Smolian, Kardjali, Pernik and Varna, Bulgaria	(Ivanova et al., 2023)	Track detector (passive) *~3–7 months*	Med: 109; GM: 114; GSD: 2.08; Min-Max: 11–1676
16 (331) *[Schools]* Plovdiv province, Bulgaria	(Ivanova et al., 2021)	Track detector (passive) *8 months*	Med: 100; GM: 108; GSD: 2.35; Min-Max: 24–995
174 (777) *[Kindergartens]* Burgas, Pernik, and Plovdiv, Bulgaria	(Ivanova et al., 2017)	Track detector (passive) *3 months*	Med: 164; GM: 171; GSD: 2.15; Min-Max: 20–1117
296 (922) *[Kindergartens]* Sofia, Bulgaria	(Ivanova et al., 2014)	Track detector (passive) *3 months*	Med: 98; GM: 101; GSD: 2.08; Min-Max: 9–1415
32 (NR) *[Kindergartens]* Iceland	(Jónsson et al., 2015)	Track detector (passive) *3–6 months*	Med: 6; GM: NR; GSD: NR; Min-Max: ~3–~52
3 (9) *[School and a kindergarten]* Kozani, Greece	(Kalimeri et al., 2016)	Track detector (passive) *4 weeks, two measurements in heating and non-heating periods*	Med: NR; GM: 40 (non-heating), 43 (heating); GSD: NR; Min-Max: 11–84
45 (45) *[Schools]* Adapazari, Turkey	(Kapdan and Altinsoy, 2014)	Track detector (passive) *75 days*	Med: NR; GM: NR; GSD: NR; Min-Max: 33–151
14 (14) *[Schools]* Tuzla, Bosnia and Herzegovina	(Kasić et al., 2024)	Track detector (passive) *95–126 days*	Med: NR; GM: NR; GSD: NR; Min-Max: 6.8–143
1809 (NR) *[Schools and kindergartens]* 192 municipalities, Finland	(Kojo and Kurttio, 2020)	Track detector (passive) *>2 months*	Schools (n = 1176): Med: 41; GM: 42; GSD: NR; Min-Max: NR–4205 Kindergartens (n = 633): Med: 40; GM: 39; GSD: NR; Min-Max: NR–2426
1010 (NR) *[Schools]* Switzerland	(Kropat et al., 2014)	Track detector and Electret (passive) *~3 months*	Med: NR; GM: NR; GSD: NR; Min-Max: ~145–~172*
2 (3) *[Nurseries]* Poznań, Poland	(Kubiak and Basińska, 2023)	Pulsed ionization chamber (passive) *~1.5–6 months*	Med: 31.2–44.8; GM: NR; GSD: NR; Min-Max: 0.3–238.8
12 (42) *[University]* Kahramanmaraş province, Turkey	(Küçükönder, 2022)	Continuous radon monitor (active) *10 min*	Med: NR; GM: NR; GSD: NR; Min-Max: 8 ± 3–26 ± 9
67 (952) *[Schools]* Campania, Italy	(La Verde et al., 2023)	Track detector (passive) *1 year*	Med: NR; GM; NR; GSD: NR; Min-Max: 18–1060 (building averages)
39 (525) *[Schools and kindergartens]* Salento, Italy	(Loffredo et al., 2022)	Track detector (passive) *6 + 6 months*	Med: 74; GM:77; GSD:2; Min-Max: 11–1416
1 (17) *[School]* Ponte de Lima, Portugal	(Lopes et al., 2018)	Continuous radon monitor (active) *7 days*	Med: ~100–1478.1; GM: NR; GSD: NR; Min-Max: ~0–~3300
18 (79) *[Schools]* Tenerife, Canary Islands, Spain	(López-Pérez et al., 2022)	Track detector (passive) ~3 months	Med: ~15-~225; GM: NR; GSD: NR; Min-Max: ~15–~355
13 (45) *[Schools]* Porto, Portugal	(Madureira et al., 2016)	Track detector (passive) ~2 months	Med:154; GM: NR; GSD: NR; Min-Max:56–889
419 (NR) *[Schools]* Lecce, Italy	(Maggiore et al., 2020)	Track detector (passive) *6 + 6 months (n = 332), 6 months (n = 87)*	Med: 155; GM: NR; GSD: NR; Min-Max: 21–1608
30 (NR) *[Schools and kindergartens]* Niš, Serbia	(Manić et al., 2019)	Activated carbon (active) *NR*	Med: NR; GM: NR; GSD: NR; Min-Max: 15–256

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Table 3 (*continued*)

Number of buildings (number of rooms) *[Type of buildings]* City/area, Country	Reference	Sampling method (active/passive) *Sampling time*	Indoor radon concentrations (Med, GM, GSD, Min-Max + other statistics if reported)
17 (58) *[Kindergartens]* Slovakia	(Müllerová et al., 2022)	Track detector (passive) *4x3 months*	Med: NR; GM: NR; GSD: NR; Min-Max: 75–1810
5 (23) in Hungary; 8 (23) in Poland; 7 (21) in Slovakia *[Kindergartens]* Hungary, Poland and Slovakia	(Müllerová et al., 2019b)	Track detector (passive) *4x3 months*	Med: 111–138; GM: NR; GSD: NR; Min-Max: 12–1333
4 (10) *[Kindergartens]* Central and Western Slovakia	(Müllerová et al., 2019a)	Track detector (passive) and Continuous radon monitor (active) *4x3 months (passive), 1 month (active)*	Track detector: Med: NR; GM: NR; GSD: NR; Min-Max: ~75–~1375
5 (23) in Hungary; 8 (23) in Poland; 7 (21) in Slovakia *[Kindergartens]* Hungary, Poland, and Slovakia	(Müllerová et al., 2017)	Track detector (passive) *3 + 3 months*	Hungary: Med: 238; GM: 231; GSD: NR; Min-Max: 64–524 Poland: Med: 73; GM: 78; GSD: NR; Min-Max: 31–200 Slovakia: Med: 195; GM: 214; GSD: NR; Min-Max: 67–1167
33 (NR) *[Schools]* Hungary, Poland, and Slovakia	(Müllerová et al., 2016)	Track detector (passive) *4x3 months*	Quarterly measured values: Med: 114–124; GM: 116–130; GSD: 2.0–2.3; Min-Max: 29–875
30 (30) *[Schools]* Kosovo	(Nafezi et al., 2014)	Scintillation cell (active), Continuous radon monitor (active), and Track detector (passive) *NR*	Med: NR; GM: NR; GSD: NR; Min-Max: 35–814
Schools: 117 (562), Kindergartens: 87 (277) *[Schools and kindergartens]* Istria, Croatia	(Radolić et al., 2019)	Track detector (passive) *1 year*	Schools: Med: 113; GM: 130.2; GSD: 2.6; Min-Max: 11–1377 Kindergartens: Med: 134; GM: 129.3; GSD: 2.3; Min-Max: 16–1288
NR (735) *[Kindergartens and schools]* Latvia	(Reste et al., 2022)	Track detector (passive) *4–6 months*	Schools (n = 397): Med: 59; GM: NR; GSD: NR; Min-Max:10–460; Q1: 36; Q3: 109 High schools (n = 35): Med: 24; GM: NR; GSD: NR; Min-Max: 4–100; Q1: 12; Q3: 44 Kindergartens (n = 393): Med: 48; GM: NR; GSD: NR; Min-Max:1–287; Q1: 32; Q3: 79
NR (62) *[Schools]* 6 communities, Spain	(Ruano-Ravina et al., 2019)	Track detector (passive) *3 months*	Med: 109; GM: NR; GSD: NR; Min-Max: NR
4 (8) *[School and nurseries]* Bragança district, Portugal	(Sousa et al., 2015)	Continuous radon monitor (active) *2–4 days*	Med: 35.05–660.16; GM: NR; GSD: NR; Min-Max: 0–888
2 (3) *[Schools]* Italy	(Stabile et al., 2016)	Continuous radon monitor (active) *7 days*	Med: NR; GM: NR; GSD: NR; Min-Max: ~0–~400
42 (42) *[Schools and kindergartens]* Kragujevac, Serbia	(Stajic et al., 2015)	Discriminative radon/thoron (UFO) detectors (passive) *3 months*	Med: 54.5; GM: 55.1; GSD: 1.18; Min-Max: 25–145
Skopje: 33 (33), Banja Luka: 25 (25) *[Schools]* Skopje, Republic of North Macedonia and Banja Luka, Republic of Srpska	(Stojanovska et al., 2020)	Track detector (passive) *3 months (Skopje) and 1 year (Banja Luka)*	Skopje: Med: NR; GM:71; GSD: 2.13; Min-Max: 9–379 Banja Luka: Med: NR; GM:50; GSD: 2.11; Min-Max: 25–341
29 (58) *[Schools]* 4 municipalities, Eastern part, Macedonia	(Stojanovska et al., 2019)	Track detector (passive) *~ 5 months*	Med: NR; GM: 96; GSD: 2.47; Min-Max: 10–508
31 (31) Schools 5 (NR) Kindergartens *[Schools and kindergartens]* 3 municipalities, Macedonia	(Stojanovska et al., 2016b)	Track detector (passive) *~ 11 months*	Schools (n = 31): Med: NR; GM: 134; GSD: 2.76; Min-Max: NRKindergartens (n = 5): Med: NR; GM: 125; GSD: 2.16; Min-Max: NR
29 (29) *[Schools]* 3 municipalities, Macedonia	(Stojanovska et al., 2016a)	Track detector (passive) *9 + 12 months*	9 months: Med: 109; GM: 128; GSD: 2.72; Min-Max: 24–962 12 months: Med: 115; GM: 129; GSD: 2.76; Min-Max: 22–990
43 (43) *[Schools]* 5 municipalities, Macedonia	(Stojanovska et al., 2014)	Radon: Track detector (passive) Progeny: Direct radon-thoron progeny sensors (DRPS-DTPS) (passive) *3 months*	Radon: Med: 67; GM: 76; GSD: 1.7; Min-Max: 27–242 Equilibrium equivalent radon (EERC): Med: 29; GM: 27; GSD:1.4; Min-Max:8–42
59 (59) *[Schools]* Czech Republic, Hungary, Italy, Poland, and Slovenia	(Szabados et al., 2021)	Track detector (passive) *3 months*	Med: 55; GM: NR; GSD: NR; Min-Max: 9–507; P5: 21; P95: 304
2 (NR) *[Schools and kindergartens]* Aqsu, Kazakhstan	(Tokonami et al., 2023)	Track detector (passive) *3 months*	Aqsu (Kindergartens): Med: NR; GM:NR; GSD:NR; Min-Max:

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Table 3 (*continued*)

Number of buildings (number of rooms) *[Type of buildings]* City/area, Country	Reference	Sampling method (active/ passive) *Sampling time*	Indoor radon concentrations (Med, GM, GSD, Min-Max + other statistics if reported)
			NR–1035 Aqsu (Elementary school): Med: NR; GM:NR; GSD:NR; Min-Max: 246–954
17 (171) *[Schools and kindergartens]* Lecce, Italy	(Tunno et al., 2017)	Track detector and Electret (passive) *6 months (Track detector), 2 + 2 weeks (Electret)*	Med: NR; GM: NR; GSD: NR; Min-Max: 121–2424
24 (NR) *[Schools (all levels) and kindergartens]* Cappadocia, Turkey	(Turhan et al., 2017)	Continuous radon monitor (active) *NR*	Summer: Med: 60; GM: 58; GSD: NR; Min-Max: 20–217 Winter: Med: 54; GM: 54; GSD: NR; Min-Max: 17–219
26 (26) *[Schools and kindergartens]* Slovenia	(Vaupotič et al., 2017)	Track detector, different types (passive), Scintillation cell and Continuous radon monitor (active) *~1-~4 months (track detector), NR (Scintillation cell), and 7–12 days (Continuous radon monitor)*	Scintillation cell (n = 26): Med: NR; GM: NR; GSD: NR; Min-Max: 30 ± 12–6870 ± 120 Track detector (n = 8): Med: NR; GM: NR; GSD: NR; Min-Max: 235 ± 20–5300 ± 270 Continuous monitor (n = 9): Med: NR; GM: NR; GSD: NR; Min-Max: 260–4580*
507 (3345) *[Pre-university education buildings]* Montenegro	(Vukotic et al., 2019; Zekić et al., 2020)	Track detector (passive) *9 months*	Med: 129; GM: 142; GSD: 1.09; Min-Max: NR–>3600
NR (68) *[University]* Sakarya, Turkey	(Zenginerler et al., 2016)	Track detector (passive) *NR*	Med: NR; GM: NR; GSD: NR; Min-Max: 0.20 ± 0.04–94.1 ± 10

NR = not reported.

Table 4

Percentages of reported median and maximum concentrations exceeding the European regulatory limit (300 Bq/m^3) and the WHO's recommended indoor radon reference level (100 Bq/m^3) in kindergartens and educational facilities in various European countries.

	Concentrations exceeding European regulatory limit (300 Bq/m^3)	**Concentrations exceeding WHO's reference level (100 Bq/m^3)**
Median concentrations		
All (n = 63)	4.8 %	55.6 %
Passive sampling (n = 49)	2.0 %	55.1 %
Active sampling (n = 14)	14.3 %	57.1 %
Maximum concentrations		
All (n = 79)	75.9 %	93.7 %
Passive sampling (n = 61)	77.0 %	95.1 %
Active sampling (n = 18)	72.2 %	88.9 %

buildings were excluded from our quantitative analyses.

Of the studies examined, 4.8 % reported median radon concentrations exceeding the European regulatory limit of 300 Bq/m^3 (Table 4). However, if the WHO's recommended indoor radon reference level of 100 Bq/m^3 is used, this percentage increases to 55.6 %. The median radon concentrations in kindergartens and educational facilities – including schools, universities and preuniversity educational facilities – exhibited a wide range: approximately 10 Bq/m^3 to 1478 Bq/m^3 for active sampling and 6 Bq/m^3 to 360 Bq/m^3 for passive sampling. The lowest and highest median values discovered with active sampling were recorded in schools in Porto and Bragança, Portugal (Branco et al., 2016), and in school buildings in Ponte de Lima, Portugal (Lopes et al., 2018), respectively. With passive sampling, the lowest median values were found in Icelandic kindergartens (Jónsson et al., 2015), and the highest were discovered in schools and kindergartens in Alba, Romania (Bican-Brisan et al., 2022).

The collected data indicated significant variability in median radon concentrations – as measured with a track detector passive sampling method – in kindergartens and other educational facilities (Fig. 4). In kindergartens, the median radon values ranged between 6 Bq/m^3 (Jónsson et al., 2015) and 275 Bq/m^3 (Cenova et al., 2017), with the highest median concentrations observed in 91 kindergartens in Plovdiv, Bulgaria (Cenova et al., 2017). In about 50 % of the studies that reported median concentrations separately for kindergartens (using passive sampling with track detectors), the median concentrations exceeded the WHO's recommended indoor radon reference level of 100 Bq/m^3. The 10/90 and 25/75 percentiles of median values in kindergartens were 40–238 Bq/m^3 and 52–164 Bq/m^3, respectively.

In studies that reported median concentrations measured using passive sampling with track detectors, – specifically for school buildings, the median radon values ranged between 24 Bq/m^3 (López-Pérez et al., 2022; Reste et al., 2022) and 210 Bq/m^3 (Branco et al., 2016). The lowest median concentrations were measured in Latvia (Reste et al., 2022). In approximately 58 % of these studies, the median concentrations exceeded the WHO's recommended indoor radon reference level of 100 Bq/m^3. The calculated 10/90 and 25/75 percentiles of the median values in school buildings were 41–155 Bq/m^3 and 59–124 Bq/m^3, respectively.

The geometric means for radon concentrations measured using active or passive methods in kindergartens and other educational facilities ranged between 86 Bq/m^3 and 308 Bq/m^3 (for active sampling) and between 39 Bq/m^3 and 313 Bq/m^3 (for passive sampling). The lowest and highest geometric mean values recorded using active sampling were in schools and kindergartens in Chisinau Municipality, Republic of Moldova (Coretchi et al., 2023), and in schools, kindergartens and a nursery in Cluj and Constanta, Romania (Dobrei et al., 2024), respectively. With passive sampling, the lowest and highest geometric mean values were found in kindergartens in Finland (Kojo and Kurttio, 2020) and in schools and kindergartens (results include both school and kindergarten measurements) in Alba, Romania (Bican-Brisan et al., 2022), respectively (Fig. 5). In kindergarten specific studies, where passive sampling with track detectors was used, the geometric mean radon values varied between 39 Bq/m^3 (in Finland) 231 Bq/m^3 (in Hungary) (Müllerová et al., 2017). In 69 % of these studies the reported geometric mean values exceeded the WHO's recommended indoor radon reference level of 100 Bq/m^3. In kindergarten-specific studies, where passive sampling with track detectors was used, the reported 10–90 and 25–75 percentile geometric mean values were 52–230 Bq/m^3 and 88–171 Bq/m^3, respectively.

In studies that reported geometric mean concentrations in schools where passive sampling with track detectors was used, the geometric

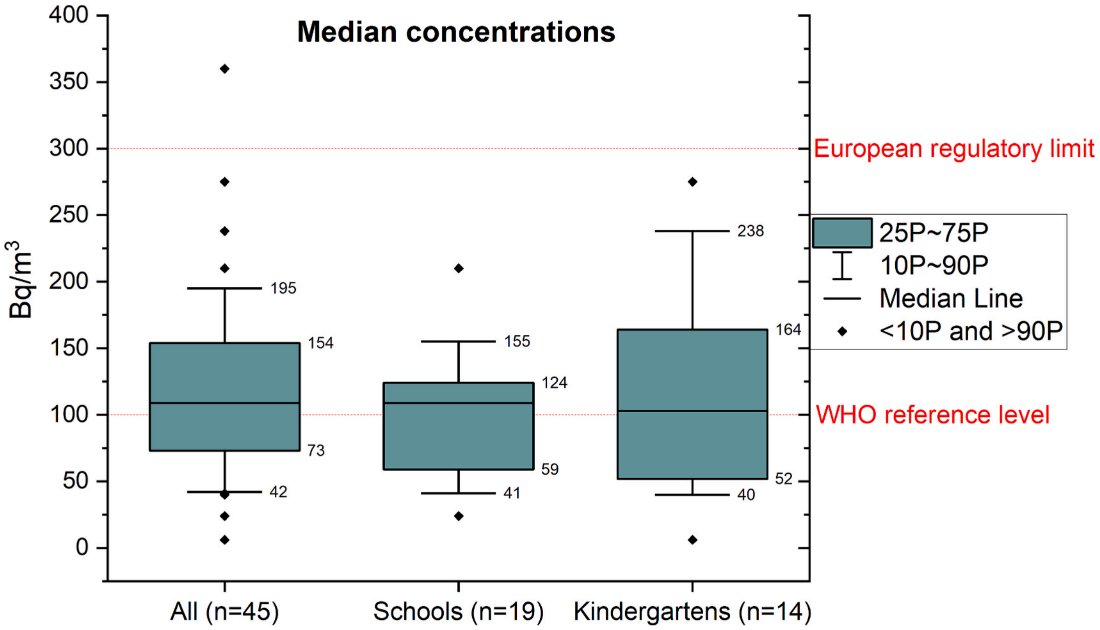

Fig. 4. Box-whisker plot of reported median radon concentrations (collected from 45 studies) in kindergartens and other educational facilities. Only passive track detector measurement data are included.

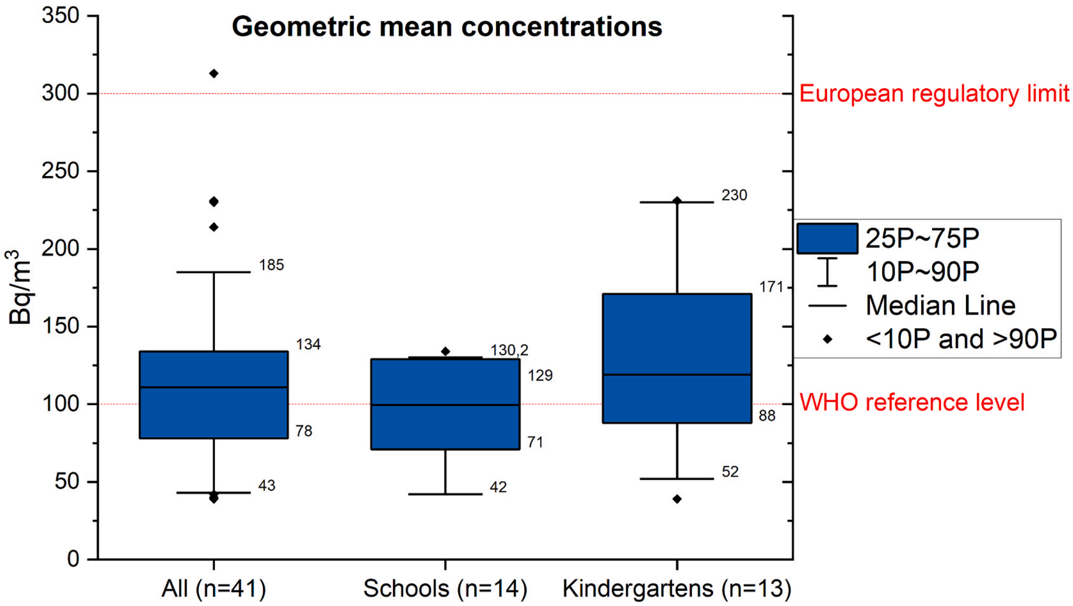

Fig. 5. Box–whisker plots of reported geometric mean radon concentrations (available from 41 studies) in kindergartens and educational facilities. Data from passive sampling measurements with track detectors data are considered.

mean radon values ranged between 42 Bq/m^3 (Damla and Aldemir, 2014) and 134 Bq/m^3 (Stojanovska et al., 2016b): the highest concentrations were measured in Macedonia. In about 50 % of these school studies, the reported concentrations exceeded the WHO's recommended indoor radon reference level of 100 Bq/m^3. In school studies, where passive sampling with track detectors was used, the reported 10–90 and 25–75 percentile geometric mean values were 42–130.2 Bq/m^3 and 71–129 Bq/m^3, respectively.

When discussing such data, it is important to ensure a correct interpretation. Our statistical analysis, presentation and argumentation are, of course, limited to the information available in the studies referenced. This information mainly includes medians and geometric means. So, when we say that a certain percentage of median values exceeds an assessment value, this says little about the absolute number or percentage of individual measurements that exceed this assessment value. The reader must be aware that the box-whisker plots in Figs. 4 and 5 refer to percentiles of medians and geometric means from the selected studies not individual measurements. Thus, the only conclusion that can be drawn from Fig. 4 is that at least 50 % of the measurements from the studies considered exceed the respective percentile. Another important point concerns the different experimental conditions of the studies. Although Figs. 4 and 5 include only passive sampler measurements with track detectors, our evaluations should be interpreted as indicative trends rather than definitive values.

In over 40 % of state kindergartens in some regions, the geometric mean radon concentrations exceeded 300 Bq/m^3 (Cenova et al., 2017).

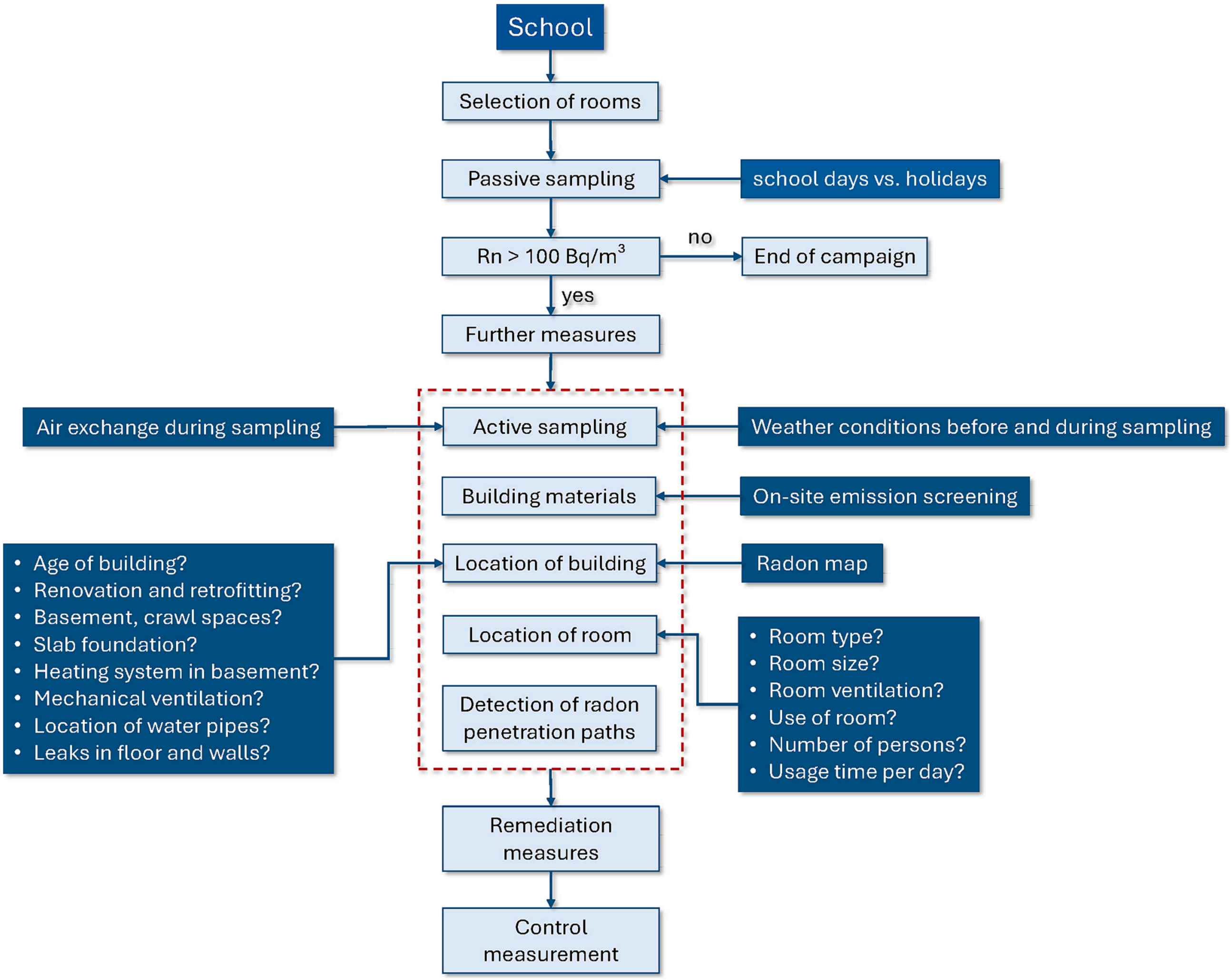

Fig. 6. A strategy for measuring and assessing radon in kindergartens and other educational facilities with suspected high levels. This strategy can also be used for routine control.

In many studies, the maximum radon concentrations exceeded 1000 Bq/m^3, with geometric means and medians varying significantly between locations (Coretchi et al., 2023; Csordás et al., 2021; Kojo and Kurttio, 2020; Nazaroff, 1992; Zekić et al., 2020). This underscores the need for regular, comprehensive monitoring of radon in kindergartens. Geometric mean radon concentrations in school buildings varied notably. There were differences between schools in the same area and between schools and homes in the same area (Vukotic et al., 2020; Zekić et al., 2020). For example, Zekić et al. (2020) identified a geometric mean radon concentration of 142 Bq/m^3 in schools, which was more than double the corresponding values for residences in the same area. Madureira et al. (2016) reported median radon concentrations between 31 and 313 Bq/m^3 for schools in Porto. In a Finnish school study the median radon level was just 41 Bq/m^3, but 14 % of schools exceeded 300 Bq/m^3 (Kojo and Kurttio, 2020). Yet another study found that nearly one-third of monitored schools exceeded the European reference limit of 300 Bq/m^3 (Branco et al., 2023).

The radon levels reported in kindergartens and educational facilities are generally significantly higher than those measured in apartment units (Alkan and Karadeniz, 2014; Cenova et al., 2017; Radolić et al., 2019; Zekić et al., 2020). For instance, Radolić et al. (2019) discovered that radon concentrations in kindergartens were approximately twice as high as those in homes, with a geometric mean of 130 Bq/m^3 in kindergartens compared to 66 Bq/m^3 in homes.

This variability in radon levels highlights the importance of regular monitoring and custom mitigation strategies in school buildings to guarantee safe indoor air quality for students and staff. There is also a need to monitor radon concentrations in multiple rooms on each floor due to the observed variation in radon concentrations between and within floors.

3.4. Occupant exposure to radon in kindergartens and other educational facilities outside Europe

Outside Europe, radon concentrations display significant variability, as they are influenced by local conditions and building characteristics. A systematic review of indoor radon concentrations in China from 2000 to 2020 reported a population-weighted median concentration of 39 Bq/m^3 in school buildings (Su et al., 2022). In a study of 37 kindergartens in Beijing, the median indoor radon level was 76.8 Bq/m^3. Of the monitoring points, 20.2 % registered levels between 100.0 and 200.0 Bq/m^3, and 2.4 % exceeded 200.0 Bq/m^3 (Yao et al., 2024). Even though the levels thus remained below the national standard limit of 300 Bq/m^3, 18.9 % of the kindergartens exceeded the limit set for new constructions: 100 Bq/m^3. Moreover, the study by Yao et al. (2024) shows that there are significant differences in indoor radon levels between various floors, with the highest concentration observed on the ground floor. Consequently, enhancing radon monitoring in China and establishing a national standard for permissible kindergarten levels are recommended (Yao et al., 2024).

In Chinese dwellings, radon levels varied according to season, climatic region, and building characteristics such as ventilation and decoration. Higher indoor radon concentrations were associated with colder seasons, particularly in severely cold areas, as well as with newly decorated buildings featuring closed windows and doors. Given the trend of increasing indoor radon concentrations over the past two decades, further studies focusing on school and office buildings are recommended to illuminate the environmental burden of radon-related diseases in China (Su et al., 2022).

In Utah, USA, radon levels were measured in 66 public schools, and a geometric mean concentration of 31.39 Bq/m^3 was observed Approximately 2 % of classrooms exceeded the EPA's recommended action level of 148 Bq/m^3. Effective mitigation strategies included installing new heating, ventilation and air conditioning systems and ensuring that they remained operational (Davis et al., 2020). A review of radon regulations and statutes in US schools identified inconsistent policies across states, which could result in high radon exposure in some areas (Gordon et al., 2018).

In Russia, kindergartens demonstrated moderate radon levels, which were affected by various building factors (Onishchenko et al., 2017). A survey carried out from 2013 to 2016 in the Sverdlovskaya Oblast region of Russia measured indoor radon concentrations in 180 kindergartens. The results indicated a geometric mean of 42 Bq/m^3 (Onishchenko et al., 2017). The radon levels were influenced by building factors, and one kindergarten with high radon levels underwent a detailed evaluation.

In the Al-Najaf province of Iraq, radon concentrations in 100 primary schools ranged from 7.47 to 44.84 Bq/m^3, yielding a geometric mean of 20.67 Bq/m^3 (Dosh et al., 2023). The associated radiological parameters were within normal limits, according to data from the International Commission on Radiological Protection, the United Nations Scientific Committee on the Effects of Atomic Radiation and the National Council on Radiation Protection and Measurements.

Zhukowsky et al. (2018) reviewed national and regional radon surveys of schools and kindergartens in Asia, Europe, Africa and North America. Based on the data, they estimated that in 1.5 % of these educational facilities, radon concentrations exceed 300 Bq/m^3. Additionally, a population-weighted global geometric mean value of 36 Bq/m^3 was calculated for radon concentrations in educational facilities based on data from multiple countries. This value was significantly lower than the geometric mean calculated for the European subset of their data (84 Bq/m^3).

3.5. Determinants of radon concentrations in European kindergartens and other educational facilities

We have shown that the temporal courses of radon concentrations in indoor spaces depend strongly on the conditions in place. To analyse this variability in more detail, the references listed in Table 3 were evaluated against and supplemented by further studies. Important points from this investigation – which are also relevant for the later introduction of an assessment strategy – are discussed in this section.

3.5.1. Geographical location of the building, room floor level and absence of underground floors

The geographical location of a building and certain aspects of its construction significantly influence the radon levels therein. Buildings located atop specific geological formations, especially in radon-prone areas with volcanic or granitoid rocks, demonstrate heightened radon concentrations (Bossew et al., 2014). Ivanova et al. (2017) discovered that geographical factors have a more substantial impact on radon levels in inland cities than in coastal regions.

Radon exposure in classrooms, particularly those in basements or on ground- floor levels, poses a significant health risk. Studies suggest that radon levels are usually highest in these areas because they are in direct contact with the soil (Bican-Brisan et al., 2022; Branco et al., 2016; Coretchi et al., 2023; Müllerová et al., 2019a). Interestingly, however, buildings without basements or foundations are generally correlated with higher radon levels (Azara et al., 2018; Chobanova et al., 2023; Csordás et al., 2021; Djounova et al., 2023; Ivanova et al., 2021; Ivanova et al., 2017; Ivanova et al., 2014; Müllerová et al., 2019a; Stajic et al., 2015; Stojanovska et al., 2019).

3.5.2. Construction, building materials, ventilation, and energy efficiency measures

Factors such as building materials, building age, ventilation methods and quality of clean air delivery significantly impact radon levels. Brick buildings, particularly those without basements, tend to exhibit higher radon concentrations (Ivanova et al., 2014). While the primary source of indoor radon is ^{226}Ra in soil, construction materials composed of minerals or natural rock can also emit radon (Branco et al., 2024; Chobanova et al., 2023; Csordás et al., 2021; Ćurguz et al., 2015; Ivanova et al., 2017; Ivanova et al., 2014; Lopes et al., 2018; Reste et al., 2022; Ruano-Ravina et al., 2019). High radon concentrations have also been measured during night times, early mornings and weekends due the ventilation practices (Antunovic et al., 2023; Azara et al., 2018; Bochicchio et al., 2014; Branco et al., 2016; Dobrei et al., 2024; Fuoco et al., 2015; Kubiak and Basińska, 2023; López-Pérez et al., 2022; Madureira et al., 2016; Müllerová et al., 2019a; Müllerová et al., 2017; Sousa et al., 2015).

Energy-saving measures that enhance building airtightness often result in increased radon levels, as evidenced in kindergartens (Fojtíková and Rovenská, 2014; Ivanova et al., 2023), and in an university building (Baltrėnas et al., 2020). However, ensuring appropriate ventilation when the building is occupied can help mitigate this effect. Onishchenko et al. (2017) found that low ventilation rates and tightly sealed structures result in increased radon levels when buildings are vacant. Both mechanical ventilation systems and consistent natural ventilation have been shown to effectively reduce indoor radon levels (Müllerová et al., 2019b; Reste et al., 2022).

The date of building's construction also impacts the radon concentrations therein. Müllerová et al. (2019a) reported that kindergartens built before 2000 have significantly higher radon levels than those constructed after 2000. Buildings constructed between 1946 and 1989, often using materials such as slag and fly ash, exhibit heightened radon concentrations (Csordás et al., 2021).

3.5.3. Behaviours of occupants and the use of rooms

The behaviour of occupants, such as the frequency with which they open windows and doors, can significantly impact indoor radon levels. For instance, in naturally ventilated schoolrooms, radon concentrations decrease when windows are open and increase when they are closed (Bican-Brisan et al., 2022). In one case, Azara et al. (2018) observed that radon levels rose overnight and during breaks when classrooms were closed.

Maintaining standard operating schedules in kindergartens, including mandatory ventilation routines and outdoor activities, can help to effectively manage radon exposure levels (Onishchenko et al., 2017). Furthermore, maintaining sufficient ventilation and avoiding materials prone to cracking, such as terra cotta, can reduce radon levels (Chobanova et al., 2023).

3.5.4. Season

Radon emanates from soil in concentration that vary with the season and geographical location (Baskaran, 2016). Indoor radon concentrations also typically display a seasonal patterns, with higher levels recorded during colder months (Belete and Shiferaw, 2022). The seasonal variations are influenced by factors such as temperature, weather conditions, living habits and occupancy patterns (Carlo et al., 2018; Müllerová et al., 2019b). Some studies have reported increased radon levels during warmer months because of varying ventilation practices (Branco et al., 2023; Müllerová et al., 2019a). In kindergartens, seasonal variation in radon levels is less pronounced than in residential dwellings, largely due to more consistent ventilation practices and closure periods being in place during summer breaks (Csordás et al., 2021).

This listing makes clear that several factors contribute to the variability of indoor radon concentrations in educational facilities. These are summarized in Table S7 and must also be considered in mitigation strategies (see Fig. 6).

3.6. Radon regulations and mitigation strategies

An overview of radon regulations and management strategies in the Nordic countries was recently published in the Nordic-Nat Report 01-2024 (Finne et al., 2024). The application to new buildings or limits or reference values for radon varies in these countries. In Denmark, the limit of 100 Bq/m^3 applies to the entire lifespan of the building. Finland sets the reference value for new buildings at 10 years after completion. In Norway, the regulations are valid until the completion certificate is issued, with a general warranty period of 5 years. Sweden requires compliance in a way that ensures the standard can be met for the building's expected lifespan with normal maintenance, according to the Planning and Building Act. However, upgrades are not required if stricter regulations are introduced later.

Preventive measures against radon are handled differently in each country. In Norway, mandatory solutions for prevention are explicitly included in the regulations. In Denmark, Finland and Sweden, guidance materials accompany the relevant regulations to help meet the limit or reference values through preventive measures (Finne et al., 2024). In Finland, the building code and practical guidelines for radon prevention underwent revisions in 2003–2004. Since then, preventive measures have become more widespread and effective, significantly reducing indoor radon concentrations in buildings constructed after 2006 (Nikkilä et al., 2020).

In Germany, a reference value of 300 Bq/m^3 for the annual average ^{222}Rn concentration in residential and workspaces is set by the Radiation Protection Act (Fromme et al., 2019). Heinzl et al. (2024) determined a population-weighted 95th percentile of 141 Bq/m^3 after correcting the data from the 2019–2021 German National Radon Survey (Kemski et al., 2024) for long-term exposure. German federal states are required to designate areas in which high radon concentrations are expected as radon precaution areas. Within these precautionary areas – particularly in new buildings and workplaces – stricter protections against radon are enforced. Based on information provided by the states, the Federal Office for Radiation Protection generates a regularly updated radon map. Petermann et al. (2024) employed a machine learning-based probabilistic quantile regression forest model to analyse the German 2019–2021 data. This enabled the creation of a high-resolution radon map for Germany, allowing for a more accurate prediction of indoor radon concentrations than would be possible using descriptive statistics.

There is an extensive programme in place for measuring radon in the US (George, 2015). The EPA has developed a map of three radon zones to identify areas with potentially elevated indoor levels, which Jones et al. (2018) used to conduct a risk assessment of schools. However, Gordon et al. (2018) criticised the lack of consistent nationwide radon policies, which, they argued, may result in unacceptably high radon levels in US schools.

3.7. Methods of reducing radon exposure in kindergartens and educational facilities

Several key strategies are used to reduce radon exposure. Proper ventilation systems are crucial, as buildings with effective ventilation display significantly lower radon levels (Angelova et al., 2023). Regular monitoring and maintenance of these systems are essential, particularly in older buildings where renovations could inadvertently increase radon levels (Cenova et al., 2017; Djounova et al., 2023). Sub-slab depressurisation and active ventilation of crawlspaces have proven effective in controlling radon levels in educational buildings (Tunno et al., 2017). The implementation of suitable ventilation measures and techniques and maintenance of school facilities can significantly decrease radon levels. Natural ventilation and ventilation education could, as suggested by Azara et al. (2018), could be a first step. However, in the medium and long terms, more technically sophisticated solutions will be required, including mechanical ventilation.

Periodic radon assessments are crucial to ensure that long-term levels stay within safe boundaries. This is evidenced, for example, by the need for repeated measurements in Czech kindergartens (Fojtíková and Rovenská, 2014). A protocol should be developed for consistent radon monitoring in all school buildings and classrooms. This protocol should be complemented by public outreach initiatives to raise awareness about radon risks and mitigation strategies (Branco et al., 2023).

Furthermore, the development of tailored radon maps and models can effectively guide mitigation efforts by highlighting high-risk areas based on geological and building data (Bossew et al., 2014). Geostatistical techniques used to produce 'school radon maps' can help identify these high-risk areas, thereby guiding targeted remediation efforts (Bossew et al., 2014).

The various studies surveyed propose different radon mitigation strategies (Khan et al., 2019; Nunes et al., 2022). For instance, one approach involves using insulation materials, such as special paints and screens to prevent radon from seeping into indoor spaces from the ground. These materials can be used in both the renovation of existing buildings and in new constructions. Another effective measure, when feasible, is the construction of airboxes between the ground and floors or walls (Richter et al., 2021; Szajerski and Zimny, 2020).

Based on our analysis and evaluation of the available literature, Fig. 6 identifies a strategy for measuring and assessing radon in educational facilities suspected of having elevated radon levels; this strategy can also be used in buildings that require regular monitoring. Our approach benefits from the design of a study conducted in 2017 at schools in the state of Baden-Württemberg, Germany (Fesenbeck et al., 2017).

3.8. Unique viewpoints: a comparative exploration of radon concentrations in European kindergartens and educational facilities

To our knowledge, this is the only study to have collected comprehensive data on indoor radon concentrations in kindergartens and other educational buildings in Europe. Thus, our study offers a novel perspective by focusing on these locations, which have been examined less often than residential buildings. Our work unveils fresh insights primarily due to our systematic and consistent collection of information on these facilities. Using a diverse collection of search terms and databases led to a comprehensive set of data that was meticulously analysed. This assessment suggests that potentially harmful radon levels are present in these settings, which highlights the necessity of regular testing and mitigation strategies. Unlike previous studies (see Table S2 in the Supplementary Material), our research employed a detailed approach, unearthing patterns that suggest higher radon concentrations in kindergartens. Fig. 6 illustrates the measurement and assessment strategy for measuring and assessing radon in kindergartens and other educational facilities in which high radon levels are suspected or where routine monitoring appears necessary. The proposed assessment strategy provides an effective, practical framework for appropriately mitigating the potential health risks associated with this radioactive noble gas.

3.9. Study limitations

While our study provides valuable insights into indoor radon concentrations and exposure in kindergartens and educational buildings, it is essential to acknowledge several limitations that may affect the interpretation of the findings. First, the analysis relies on median and geometric mean values extracted from existing literature rather than raw individual-level data, which may obscure nuances present in detailed datasets. Additionally, there was inherent heterogeneity in the sampling methods and durations employed across the different studies, which could have affected the consistency and reliability of our comparisons. The use of summarised values, such as medians, to estimate proportions exceeding specific thresholds also limits the precision of the results. Furthermore, discrepancies between passive and active sampling methods make direct comparisons challenging and may have introduced bias. Recognising these limitations is crucial for situating the results within the broader research context and suggesting pathways for future investigations.

4. Conclusions

Our research reveals highly concerning radon concentrations in European kindergartens and other educational facilities. In 5 % of the reviewed studies, the reported median concentrations exceeded the European regulatory limit (300 Bq/m^3), while 56 % of the median concentrations exceeded the WHO's recommended reference level (100 Bq/m^3). A distinctive aspect of our investigation, in comparison with existing radon reviews, is the focus on these educational spaces, which have often been overlooked in prior studies.

The concentrations highlighted in our review emphasise the urgency of standardized assessment methods, regular monitoring and comprehensive mitigation strategies. These strategies should account for various influencing factors, such as soil geology, building characteristics and user activities. The comparison with other reviews further emphasises the need to align national reference values with the WHO's recommended standard. Given our findings, kindergartens require particular attention due to their consistently higher radon concentrations. Our study not only fills the existing knowledge gap but also advocates for reliable policies and practices to manage children's exposure to radon. In this way, we intend to help build a safe and healthy environment for future generations.

CRediT authorship contribution statement

Heidi Salonen: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tunga Salthammer:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tuomas Alapieti:** Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation. **Ati Shirazi:** Writing – review & editing, Data curation. **Raimo Mikkola:** Writing – review & editing, Data curation. **Lidia Morawska:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109877.

Data availability

No data was used for the research described in the article.

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