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Assessment of Indoor Radon Gas Concentration in Latvian Households

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Abstract: Exposure to radon gas in households presents serious health risks, including an increased likelihood of lung cancer. Following the COVID-19 pandemic, the change in individual habits has led to more time spent in indoor environments with remote activities; thus, the need to raise the awareness of air quality in dwellings and to mitigate the exposure of inhabitants to radon has emerged. This study investigated radon gas concentrations in the air of Latvian dwellings. RadTrack2 passive detectors were deployed in a representative sample of households across 106 municipalities of Latvia (98% of the territory), yielding data from 487 households (973 detectors). The data revealed a median radon concentration of 52 Bq/m^3 (Q1 and Q3 were 29 and 93 Bq/m^3), with the majority of samples (95.6%) falling below the national reference limit of 200 Bq/m^3. The building type and presence of a cellar significantly impacted radon levels, with structures lacking cellars and older buildings exhibiting higher concentrations. Mechanical ventilation proved to be more effective in reducing radon levels, compared to natural ventilation. These findings emphasize the necessity of proactive measures to mitigate indoor radon exposure and to ensure the well-being of occupants. Additionally, the dissemination of research data on radon exposure through open-access scientific publications is vital for raising awareness and implementing effective mitigation strategies.

Keywords: aeration; age of house; floor material; households; ventilation; indoor air quality; insulation; non-occupational exposure; radon gas; vulnerable population

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1. Introduction

Throughout the entire existence of Earth, both living and non-living entities have been subjected to ionizing radiation. There are two main natural pathways through which radiation reaches us: the first originates from extraterrestrial sources—namely, cosmic radiation that penetrates our atmosphere—and the second encompasses all terrestrial sources, which cause internal and external irradiation [1]. These elements can be found in the soil, water, air, and other environments (e.g., geological formations, building materials) [2]. In this study, the authors focused on radon, as it is one of the most prevalent radionuclides on our planet and contributes to approximately half of the effective dose equivalent received from all-natural radiation sources. Such exposure may result in doses that are significantly high, raising human health concerns [1]. Moreover, radon is known to accumulate in residential spaces and is one of the main indoor air pollutants. According to the latest data from Google COVID-19 Community Mobility Trends in 2023, a notable global trend has emerged, which indicates an increase in indoor time compared to pre-pandemic levels. This suggests that individuals are spending at least 1% more time at home, potentially exposing themselves to hazardous environments [3].

Radon is a colorless and odorless chemically inert radioactive gas. Radon is a natural decay product of uranium-238 and radium-226 (Figure 1). Among the natural isotopes of radon, radon-222 has the longest half-life of approximately 3.8 days [4]. After radon-222 is inhaled, it continues to decay within the lungs. Free radon gas is able to reach the deepest areas of lungs, irradiating them. In dusty environments, there is a mixture of radon gas, its progeny, and dust, and the level of airways irradiated depends on the particulate matter size inhaled. If the diameter of the particle does not allow it to reach the alveoli, it can locally irradiate the bronchioles and bronchi [4]. Its decay results in the formation of polonium-214 and polonium-218 and delivers most of the radiation dose to the lungs. In this process, alpha and gamma radiation are emitted—predominantly alpha radiation (see Figure 1) [4,5].

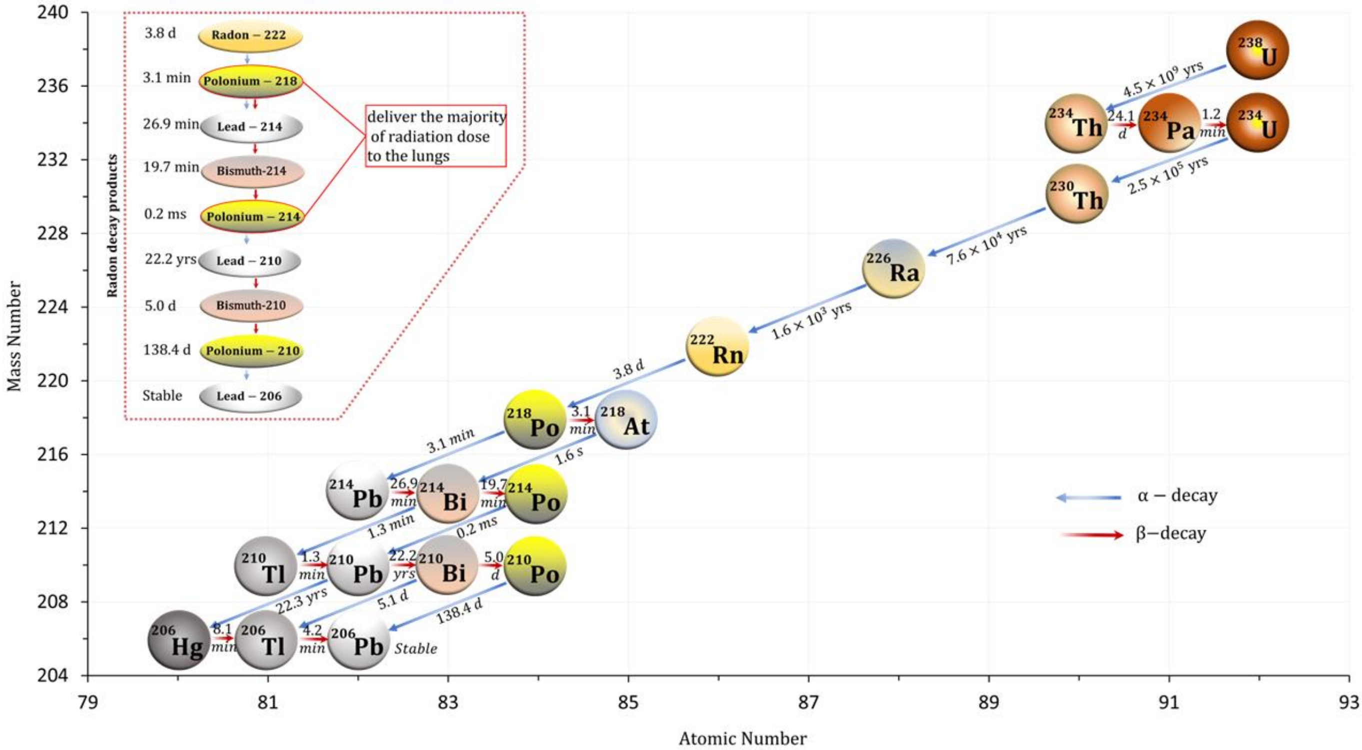

Figure 1. Scheme of Ra-222 decay series as a part of U-238 decay chain. Adapted from [6–9].

These alpha particles have low penetrating ability but can be highly destructive at short distances. Once radon-222 enters the body, the individual's exposure to radioactive decay products is heightened, primarily within the lung tissue. This exposure persists as the decay of radon-222 continues. The decay products of radon, rather than being excreted, decay further into other radioactive elements, which continue to emit radiation until they transition into stable non-radioactive forms. This leads to localized irradiation, which causes damage to biologically sensitive macromolecules such as DNA (deoxyribonucleic acid), RNA (ribonucleic acid), lipids, and proteins. Regarding the irreversible changes caused by radiation, it is known that DNA molecule damage can lead to cell death (a lethal outcome) as well as chronic consequences (non-lethal outcomes), which are the most dangerous in the long-term due to their cumulative effect. This leads to mutagenesis which, in turn, can result in the development of oncological processes or changes in gene expression [4]. Due to its carcinogenic properties, radon was recognized as a carcinogen in 1988 [10]. According to the World Health Organization (WHO) data, prolonged and excessive exposure to radon is identified as the second most significant risk factor (after smoking) for lung cancer development [11].

Numerous factors influence the radon concentration indoors, such as building materials, building construction type, the type of ventilation system which is in use, and meteorological and geological parameters [12]. In geologically low-risk countries, radon gas exposure may be perceived as less of a concern due to lower natural concentrations. However, it is crucial to maintain awareness and to implement moderation measures, as even minimal levels of radon exposure can present enduring health hazards. Radon levels can fluctuate over time, so continuous monitoring and precautionary measures are essential. Considering its carcinogenic nature, even low levels of radon exposure can pose health risks over prolonged periods, underscoring the significance of using proactive monitoring and moderation strategies to effectively mitigate the potential risks [13]. After diffusing from the soil (resulting from the decay of uranium, which is found extensively in the Earth's crust), radon enters homes through cracks in walls and floors and begins to accumulate in enclosed spaces, particularly poorly ventilated places such as basements or ground floors. Consequently, its presence can be registered in residential houses, offices, and other buildings [14].

In light of data concerning the risks associated with exposure to radon gas and its health-related significance, the initial directives of the Euratom Commission (Commission Recommendation 90/143/Euratom) [15] recognized the necessity of setting standards in the case of long-term radon exposure. Later, the recommended limit for the indoor radon concentration was set at the level of 200 Bq/m^3 [16]; the same limit was implemented in Latvian legislation [17]. Considering the newer scientific findings, which reveal that the lung cancer development risk significantly increases with chronic exposure at a level as low as 100 Bq/m^3, the Council Directive 2013/59/Euratom of 5 December 2013 recommended a revision of the existing standards and the incorporation of new limits [16,18–20]. Therefore, radon gas concentration mitigation is essential. Practical strategies—including radon gas concentration testing, the raising of awareness among inhabitants and policy makers, the implementation of sealing procedures through the removal of cracks and gaps in the foundation and floors, and adequate air ventilation, whether through natural means such as the opening of windows or through the use of mechanical systems—play a key role in the dispersion of radon gas and, ultimately, in the minimization of its accumulation [21].

This study aims to conduct a state-level investigation of the radon gas concentrations in the households of Latvia, in order to define the risk scenarios that lead to elevated radon levels.

2. Materials and Methods

2.1. Institutions Involved

The importance of assessing radon gas levels within residential spaces has been emphasized by relevant authorities [22–24]. Despite a lack of comprehensive studies in Latvia, efforts were initiated in 2016 by the Radiation Safety Centre of the State Environmental Service of the Republic of Latvia (RSC SES). The joint project, entitled "Radon gas measurements in Latvia's Households 2016", was launched to address this gap and was supported by the budget of the State Environmental Service and the International Atomic Energy Agency (IAEA) Technical Cooperation Program (TCP) national project LAT9013 "Strengthening Capacities in Nuclear and Radiation Safety and Nuclear Security", which provided measurement services and detectors. At the launch of the project, the RSC SES carried out a public information campaign inviting households to apply for free radon measurements. A total of 1099 household applications were received. Then, detectors were distributed and later collected by the eight State Environmental Service Regional boards and the RSC SES.

2.2. Course of Study

The radon risks in the country's territory were predicted based on geological mapping data [22]. The detection of radon gas was performed in 106 administrative territories in a total of 110 municipalities in Latvia (i.e., approximately 98% of the terrestrial area) during the period of January 2016 to December 2016.

The number of households was chosen proportionally to the size of population of the corresponding municipality to obtain representative samples. In total, the RSC SES with the 8 SES regional boards distributed 973 passive radon gas detectors to the households (on average, 2 detectors per household in multistory blocks of flats or detached houses). The detectors were placed inside 487 buildings by representatives of the households. In accordance with the RSC SES instructions, the detectors were placed exclusively on the first and ground floors, in places where the residents were most frequently located. On average, the measurements of radon gas lasted for 239 $\pm$ 30 days (8.0 $\pm$ 0.9 months) in every selected building. Before the detectors were distributed, each household had to sign a statement of commitment to participate in the project. Additionally, a specially designed questionnaire was filled in for every measurement site and submitted together with the returned detectors, in order to ensure careful data analysis after the harvesting of the detectors. The wide range of indoor radon gas concentrations was investigated, according to building age, presence of cellar and insulation, floor materials, type of windows and ventilation habits, and the system used.

After the removal of the detectors, the RSC SES dispatched them to an accredited laboratory in Sweden that reads the measurements of the radon gas level, in accordance with ISO 11665-4 [25]. The obtained data were analyzed together with the information from the questionnaires.

2.3. Measurement Equipment

The present study employed Radtrack2 alpha track detectors (manufactured by Radonova Laboratories AB, Uppsala, Sweden, Long Term Radon Test, URL https://radonova.com/radtrak2_world_leading_detector/ (accessed on 17 March 2024)) to assess indoor radon concentrations. Radtrack2 utilizes a continuous passive sampling technique coupled with delayed analysis. Comprising film elements housed in anti-static plastic, the device operates via radon diffusion, with the emitted alpha particles leaving tracks on the film. This passive entrapment mechanism captures radon throughout the measurement period, with the resultant film readings providing a summary of the radon levels within the buildings. Subsequently, the acquired data are processed and adjusted based on measurement duration and building size, yielding numerical values in Becquerels per cubic meter (Bq/m^3). The alpha track method, which has been adopted globally, is particularly exemplified by Radtrack2, which is recognized for its reliability in radon measurement applications.

Criteria for the placement of detectors were established to ensure reliable measurements over an extended period. The measurement sites were chosen based on the conditions and recommendations set out in the RSC SES instructions.

2.4. Data Processing and Statistics

After the measurement readings were received from the certified laboratory, they were combined with the protocol data regarding the placement sites; subsequently, they were all processed. Sensitive information concerning measurement locations underwent recoding to prevent direct identification. The data were categorized based on building type, building material, ventilation system, aeration mode, and so on, and compared accordingly. The normality of the distribution was assessed, and appropriate statistical methods were selected for non-normally distributed data, utilizing non-parametric techniques such as the chi-square test, Mann–Whitney test, and Spearman's correlation for analysis. Calculations were performed using the computer programs Microsoft® Excel® for Microsoft 365 MSO (Version 2402) and IBM SPSS Statistics version 29, with the statistical significance set at $p < 0.05$.

3. Results

The study was designed to evenly cover the entire area of the state and, ultimately, to obtain data from a representative sample of households in 96.4% of all municipalities of Latvia. Overall, 973 detectors were distributed across 487 households, but only 913 detectors were returned from 459 households (response rate 94.3%). After the data from wrongly placed detectors and the extreme values of outliers (>99th percentile) were excluded from the analysis, 891 detectors from 447 households were considered to have been correctly placed and were included in the analysis. The distribution of the median radon concentration levels by the municipalities of Latvia is given in Figure 2.

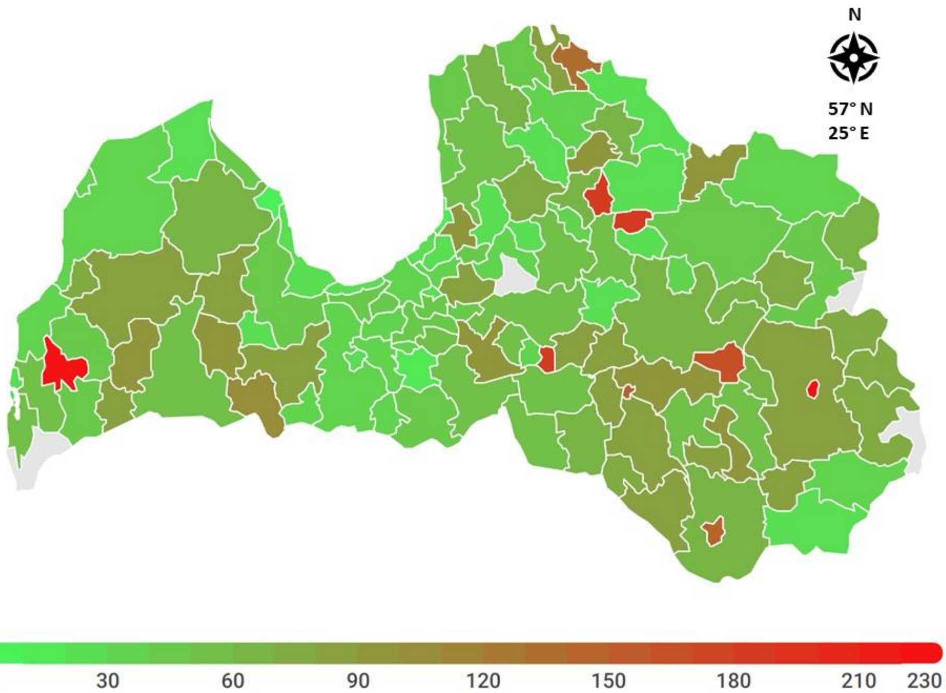

Figure 2. Median radon gas concentration in Latvian households according to municipalities (Bq/m^3). For detailed information, see the Supplementary Materials file attached.

The mean value of the radon concentrations in the air of the households was 69.8 ± 52.0 Bq/m^3 (Figure 3). The pool of data was not normally distributed and had high positive skewness (S_{sk} = 1.97, standard error SE = 0.08) and kurtosis (S_{ku} = 5.13, SE = 0.16). For this reason, further analysis included evaluation of the median values and the first (Q1) and third (Q3) quartiles using non-parametric tests. For a better estimation of the data distribution, a lognormal quantile–quantile (Q–Q) plot was assessed (Figure 3).

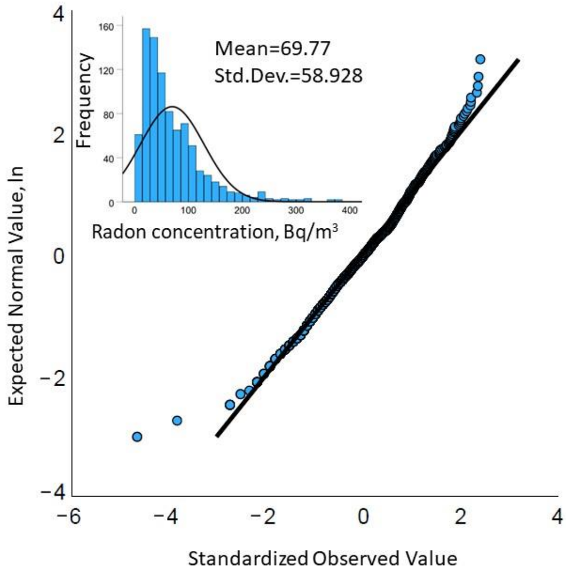

Figure 3. Q–Q plot and histogram of distribution of the radon gas concentration in the air of Latvian households (black line on histogram indicates theoretical normal distribution curve).

Most of the data in the Q–Q plot aligned with a straight line, suggesting that most of the values were approximately normally distributed. However, there were noticeable deviations at both the upper (heavy-tailed) and lower (light-tailed) ends. Despite the straight central line, the tails of the distribution appeared to lag, indicating that some of the acquired results were higher than expected, in terms of both minimum and maximum values. Usually, it is advisable to focus on deviations in the heavy-tailed region of the distribution above the median as they can have significant consequences for the health of exposed inhabitants. The deviation from lognormality in the light-tailed portion, which is frequently more pronounced, is usually less relevant to radiological issues and requires less attention [26–28].

In total, the median value of the radon concentration was slightly lower than the mean (52 Bq/m^3), with Q1 and Q3 being 29 and 93 Bq/m^3, respectively, which showed the effect of non-normal distribution and the extreme values. It is important to note that 95.6% of all the samples, when compared to the radon exposure safety limits, were within the "safe zone" below the national recommended limit of 200 Bq/m^3 for average specific radioactivity per year for indoor air in buildings [16,17]. Only 49 samples out of the total number of received detectors (n = 913) were above the national reference limit of 200 Bq/m^3, but the majority of them still did not exceed 600 Bq/m^3 (the national action limit for indoor air in buildings per year), and only one sample showed the maximal value of 704 Bq/m^3 [17].

Further analysis according to the type of building showed significant differences in the radon levels. Overall, the private detached houses had significantly higher levels of radon in their air ($p < 0.001$; Table 1). Most of the private houses had one or two floors (93.9%), while the multistory blocks of flats usually had more than three floors (67.9%). At the same time, taking all the types of houses together, the buildings with less than three floors had significantly higher levels of radon than the tall buildings (59 (31, 98) vs. 32 (22, 45) Bq/m^3; $p < 0.001$), even though all the measurements were conducted on the lowest floors. It is interesting that, in the multistory blocks of flats with less than three floors, the radon concentration was also higher than in those with more than three floors (55 (35, 95) vs. 33 (22, 49) Bq/m^3; $p < 0.001$). In the private detached houses, the situation was similar: in the lower houses, the radon levels were higher (61 (31, 99) Bq/m^3) than in the taller buildings (30 (19, 35) Bq/m^3 with more than three floors; $p < 0.001$).

The presence of a cellar also significantly influenced the levels of radon. The buildings with a cellar had significantly lower levels of radon than those without (43 (26, 81) vs. 67 (35, 106) Bq/m^3; $p < 0.001$). However, in the private detached houses, even those with the presence of a cellar, the radon levels were still higher than in the multistory blocks of flats (49 (29, 91) vs. 36 (22, 53), $p < 0.001$). It is important to note that a cellar was present in 83.9% of the multistory blocks of flats, but only in 48.5% of the private detached houses. On the other hand, in the absence of a cellar, there was no difference in radon levels between the private detached and multiapartment types of buildings ($p > 0.05$).

A weak statistically significant positive correlation between the age of the building and the levels of radon in it was found (the Spearman correlation coefficient, r_s, was 0.337, $p < 0.001$). The houses built more than 40 years ago showed significantly higher radon levels ($p < 0.001$; Table 1; Figure 4B). There was no significant difference between the houses built less than 10 years ago and those built 11–40 years ago ($p > 0.05$), although it was found that the radon level tended to increase with age. However, the difference between the new buildings and those that were more than 40 years old was statistically significant ($p < 0.001$). Overall, the median level of radon in the new buildings (7.4% of all the detectors analyzed) was the lowest; however, at the same time, it showed remarkably high variance with some quite prominent levels, indicating the presence of significant contributing factors other than building age.

Table 1. Indoor radon gas concentration according to the type of building and conditions.

Type of Household/ Building/Condition	Number of Measurements	Radon Concentration, Bq/m^3			
		Mean (±SD)	Median (Q1, Q3)	Min	Max
Private detached house	701	74.26 (±59.9)	58 (31, 98)	1	384
Multistory block of flats with more than two floors	168	53.57 (±53.67)	39 (23, 58)	2	372
Cellar					
Building with cellar	486	63.30 (±60.10)	43 (26, 81)	1	372
Building without cellar	391	78.21 (±56.83)	67 (35, 106)	5	384
Floor material					
wood	529	78.62 (±62.88)	62 (35, 101)	1	384
concrete/stone/bricks	289	57.58 (±52.48)	39 (24, 75)	7	372
Age of building					
≤10 years	64	72.33 (±80.76)	38 (23, 100)	5	368
11–40 years	389	48.97 (±37.48)	39 (24, 59)	1	247
≥41 years	413	89.34 (±65.16)	79 (43, 113)	5	384
Insulation/reconstruction					
yes	328	74.03 (±63.79)	56 (31, 97)	5	372
no	547	67.30 (±55.85)	51 (27, 90)	1	384
Ventilation					
natural	824	71.16 (±59.91)	54 (30, 94)	2	384
mechanical	50	42.66 (±31.28)	31 (21, 57)	1	124
Heating system					
central	496	61.28 (±54.88)	43 (25, 80)	2	372
stove (gas, wood)	360	82.56 (±62.75)	71 (37, 101)	5	384
electricity	16	58.88 (±56.16)	35 (14, 107)	1	192
Windows					
plastic	623	70.58 (±61.15)	52 (28, 94)	1	372
other types	252	67.18 (±50.23)	53 (31, 91)	8	326

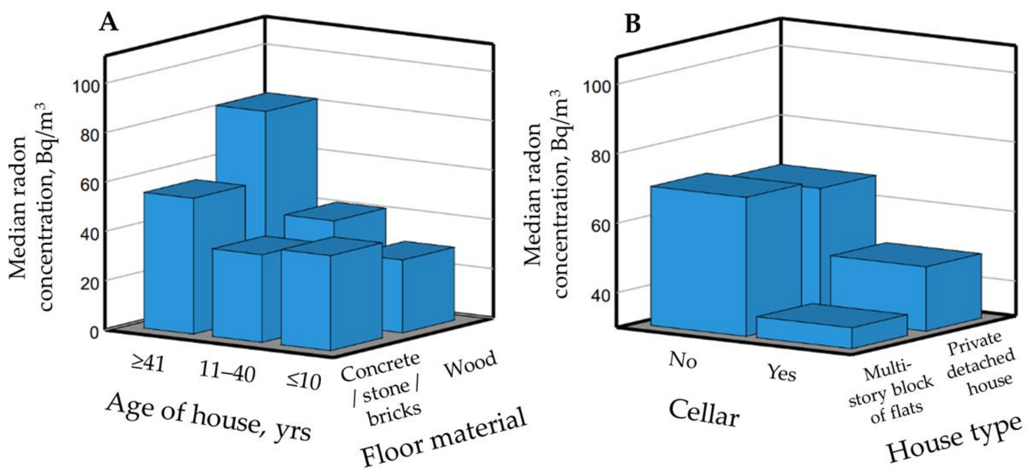

Figure 4. Radon gas concentration (Bq/m^3) in households according to age of house and floor material (**A**) and cellar and house type (**B**).

A considerable influence of floor material on the radon levels in the buildings was found. Households with wooden floors had significantly higher concentrations of radon compared to those with floors made of concrete, bricks, or stone (62 (35, 101) vs. 39 (24, 75), $p < 0.001$). This effect was particularly pronounced in the old buildings (Figure 4A).

The effect of insulation and renovation on the radon levels was less evident ($p > 0.05$), but it was observed that the insulated buildings tended to have higher levels of radon (Table 1). Only a small portion of the buildings that were more than 41 years old (35%) were insulated or reconstructed, and they showed similar levels of radon to the non-insulated old buildings ($p > 0.05$), while 75% of the buildings constructed in the past 10 years were well insulated and had significantly higher levels of radon than the non-insulated buildings of the same age ($p = 0.002$).

The type of ventilation had a remarkable impact on the radon levels in the buildings. Natural ventilation dominated in the analyzed buildings. Overall, there was natural ventilation in 92.4% of the buildings where radon detectors were placed: 94.7% of the private detached houses and 88.7% of the multistory blocks of flats. The buildings with mechanical ventilation had significantly lower levels of radon than the ones with natural ventilation (31 (21, 57) vs. 54 (30, 94), $p < 0.001$; Table 1). The duration of the aeration of the buildings during summer slightly negatively correlated with the radon levels ($r_s = -0.105$, $p = 0.002$), while the winter aeration pattern correlated less ($r_s = -0.066$, $p = 0.051$). Nevertheless, after dividing the data according to the ventilation type, it could be seen that longer aeration during winter in the buildings with natural ventilation could achieve lower radon levels than in the summer (Figure 5A,B). Mechanical ventilation with longer winter aeration patterns was more beneficial and was insignificantly correlated with the radon levels ($r_s = -0.212$, $p > 0.05$); however, if it was used in the summer for less than an hour, significantly higher levels of radon and a greater correlation with the duration of aeration could be achieved ($r_s = -0.549$, $p = 0.042$; Figure 5A).

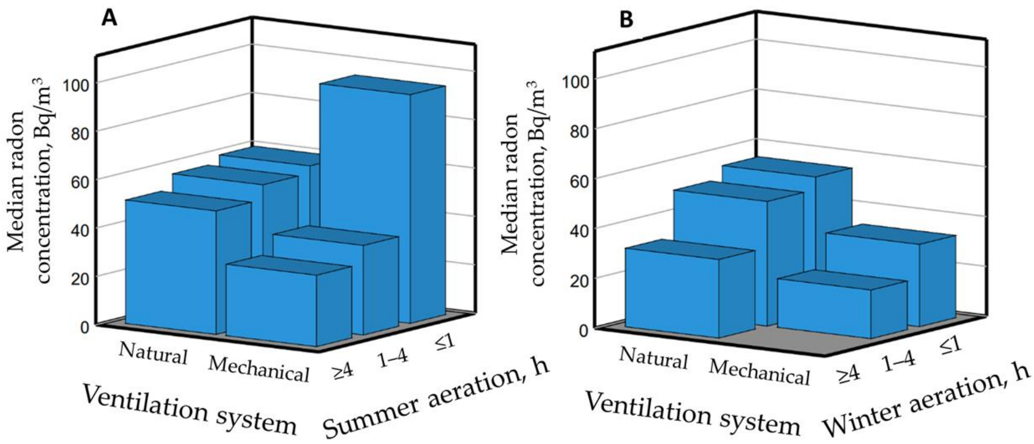

Figure 5. Radon gas concentration (Bq/m^3) in households according to ventilation type and aeration pattern in summer (**A**) and winter (**B**).

Buildings with heating systems based on stoves fueled with gas, wood, or coal had significantly higher levels of radon than those heated with electricity or central heating systems ($p < 0.001$). The stove-based heating systems were predominantly in the buildings that were more than 10 years old (62% of buildings more than 40 years old and 22% of 11–40-year-old buildings) and private detached houses (47%).

The type of room where the detector was located (bedroom, living room, or kitchen), the type of windows, and the material of the walls and ceiling did not notably affect the levels of radon in the air ($p > 0.05$).

4. Discussion

The present research assessed the indoor air radon gas concentrations in households nationwide, in alignment with the specifications outlined in Directive 2013/59/Euratom [16]. This evaluation aimed to determine whether Latvia should consider implementing further protective measures against radon, in accordance with the recommendations by global organizations. Fortunately, due to its geological profile, Latvia has a lower risk level compared to high-risk regions. However, the study revealed a nuanced landscape where factors such as building age, type, presence of a cellar, and ventilation influence radon concentrations. Although many households fell within safe limits, a fraction exceeded recommended thresholds, which indicates that there are hidden radon exposure dangers [22,29,30].

In the majority of households (95.6% of samples), the average specific concentration of radon gas in the buildings remained below the designated threshold of 200 Bq/m^3 [16,17]. Despite relatively low levels of radon gas in Latvian dwellings, it should be kept in mind that even low exposure to radon has potential long-term health effects, including an increased risk of lung cancer [11]. These findings align with the global trends, which highlight the prevalence of radon as a significant indoor air pollutant [31].

The analysis of radon levels according to building type yielded insightful results and highlighted the influence of various factors, such as building age, the presence of cellars, and ventilation systems. The private detached houses exhibited significantly higher radon levels compared to multistory blocks of flats, emphasizing the importance of building characteristics in radon mitigation efforts [32]. Additionally, buildings with cellars demonstrated lower radon concentrations, suggesting a potential role of structural design in reducing indoor radon levels [33]. The presence of a cellar can impact radon levels by allowing radon to infiltrate through the soil and penetrate through cracks in the cellar walls or floors. Conversely, if the cellar is properly ventilated with effective radon mitigation systems in place, it can serve as a buffer zone, reducing the overall radon levels in the living spaces above by venting radon gas outdoors before it can accumulate [33].

Furthermore, the study identified a weak positive correlation between building age and radon levels, with the older buildings showing higher concentrations of radon. The presence of insulation and renovation had a less pronounced effect on the radon levels. The impact of building age on radon levels can be attributed to various factors related to construction materials and structural integrity. Older buildings may have been constructed with materials that are more prone to radon penetration, such as porous concrete or stone foundations, which can allow radon to seep into indoor spaces more easily. Additionally, as buildings age, cracks and gaps may develop in the foundation or walls, providing pathways for radon to enter. Furthermore, older buildings may not have been constructed with radon-resistant techniques or may lack proper ventilation systems, increasing the likelihood of radon accumulation indoors. This underscores the importance of considering building age in radon risk assessments and mitigation strategies. The impact of ventilation systems on radon concentrations was also evident, with the buildings employing mechanical ventilation demonstrating lower radon levels compared to those relying on natural ventilation. Effective ventilation systems can help reduce radon levels in premises by diluting indoor air with outdoor air, thereby decreasing the concentration of radon gas [30,33–36]. Properly designed ventilation systems can also create positive pressure indoors, preventing radon from entering through cracks and gaps in the building. Moreover, the duration of aeration during different seasons influenced radon levels, emphasizing the importance of ventilation practices in indoor radon mitigation strategies.

Precision of the measurements depends on various factors. Uncertainty in measurements can arise from multiple aspects, leading to heightened levels of uncertainty in definite cases. Uncertainty involves deviations in indoor radon concentrations from annual averages, measured in various conditions across numerous buildings, also accounting for the influence of both natural and human-related factors, such as seasonal fluctuations in indoor radon levels and duration of measurements [34].

Radon exposure, the second greatest risk factor for lung cancer among smokers and the first risk factor for non-smokers, underscores the critical importance of reducing indoor radon levels [1–5,10,11,26,36,37]. The buildings analyzed in our current study primarily were households where individuals spent extended periods indoors, amplifying the potential impact on vulnerable populations (e.g., small children and their mothers, pregnant women on maternity leave, the elderly, and disabled non-working individuals, and schoolchildren engaged in remote learning), who may be particularly susceptible to even low levels of radon exposure over the long term. Of particular concern are children and pregnant women, who are especially sensitive to the effects of ionizing radiation, which can have lasting implications for their health throughout their lifetimes [31,37–41].

According to the regulations outlined in the "Regulations for Protection against Ionizing Radiation", it is imperative for homeowners to take proactive measures if radon levels in their households exceed the recommended limits [17]. These measures may include improving ventilation, sealing cracks in the structure, or installing underfloor ventilation systems. Additionally, periodic testing and re-testing, especially following renovations or changes in building usage, are essential to ensure ongoing radon mitigation efforts.

Overall, this study provides valuable insights into the prevalence and distribution of radon gas in residential environments in Latvia. Through tailored interventions and deeper understanding, Latvia's example offers insights for the navigation towards safer indoor environments, where awareness and action intertwine in the ongoing quest for radon mitigation. The findings of this study underscore the pervasive presence of radon gas in indoor environments and its potential health implications for residents. By disseminating accessible information about radon sources, health effects, and mitigation strategies, these studies empower individuals to take proactive steps to protect themselves and their families. Moreover, such studies can be used to advocate for policy changes and regulations aimed at reducing radon exposure levels in dwellings. Ultimately, the dissemination of accurate and understandable information through scientific studies plays a crucial role in the safeguarding of public health and the prevention of radon-related illnesses.

5. Conclusions

This study highlighted the pervasive presence of radon gas in indoor environments in Latvia and its potential health implications for residents nationwide. While the majority of households in Latvia maintained radon levels below the designated threshold, there remained a fraction that exceeded the recommended limits, highlighting the need for ongoing surveillance. Certain specific conditions identified in our study place households at risk, even under favorable geological circumstances: private detached houses that lack cellars, have wooden floors, were constructed more than 40 years ago, rely on natural ventilation, and are equipped with stove heating systems fueled by gas, wood, or coal were found to be particularly susceptible. These insights underscore the importance of considering a range of building characteristics, ventilation systems, and seasonal variations when formulating effective radon mitigation strategies. By addressing these factors comprehensively, stakeholders can better safeguard against poor indoor air quality and mitigate the potential health risks associated with radon exposure.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos15050611/s1. Table S1: Radon gas concentration levels in households by municipality in Latvia (Bq/m^3).

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BSS	Basic Safety Standards
DNA	Deoxyribonucleic acid
EPA	Environmental Protection Agency
IAEA	International Atomic Energy Agency
IARC	International Agency for Research on Cancer
IOSEH	Institute of Occupational Safety and Environmental Health
MEPRD	Ministry of Environmental Protection and Regional Development
Q–Q	Quantile–quantile
RNA	Ribonucleic acid
RSC SES	Radiation Safety Centre State Environmental Service of the Republic of Latvia
RSU	Rīga Stradiņš University
TCP	Technical Cooperation Program
WHO	World Health Organization

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