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Exploring the long-term balance between radon mitigation systems and human behaviour in Romanian houses

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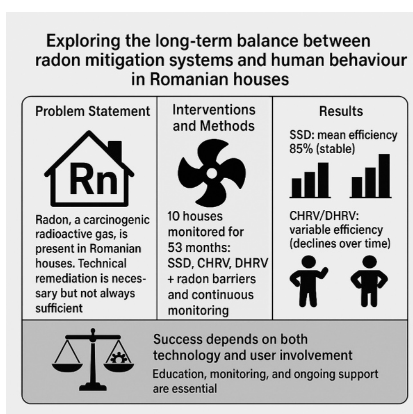
HIGHLIGHTS

- Long-term radon monitoring was conducted over 53 months in 10 Romanian homes.
- Sub-slab depressurization systems showed stable performance over time.
- User behaviour significantly influenced the effectiveness of mitigation systems.
- Continuous monitoring enabled timely detection of system failures.
- Technical solutions alone are not sufficient for sustained radon control.

GRAPHICAL ABSTRACT



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ABSTRACT

Radon is a naturally occurring radioactive gas that has high carcinogenic potential and may constitute a significant public health problem. The long-term effectiveness of radon mitigation systems is often assumed, yet rarely questioned beyond initial implementation. This study investigates the long-term performance of mitigation systems after installation, based on continuous monitoring conducted over several years. Ten Romanian dwellings served as case studies illustrating the interaction between technical remediation measures and various

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patterns of occupant behaviour. The remediation methods included sub-slab depressurization (SSD), heat recovery ventilation, both centralized (CHRV) and decentralized (DHRV), and the use of radon barriers.

The results showed a variable efficiency of the remediation methods, with average radon concentration reduction values ranging from −8 % to 91 %, and an overall median of 59 %. The SSD-based remediation methods demonstrated superior performance and better stability over time, recording an average efficiency of 86 %, while the CHRV and DHRV systems showed much higher variability and a decline in efficiency over time. One of the most critical factors contributing to the success of the remediation was user behaviour, with intermittent use, disconnecting of systems, or lack of maintenance leading to increases in post-remediation radon concentration, in some cases even above pre-remediation levels. In contrast, the active involvement of the occupants, including constant monitoring and prompt reaction to malfunctions, ensured that low radon levels (below 50 Bq/m^3) were maintained.

The findings suggest that maintaining low radon levels over time requires more than just technical interventions, highlighting the importance of a balanced interaction between automated systems and occupant engagement. These results highlight the need for public policies that combine engineering solutions with behavioural, educational, and ongoing support strategies to maintain the effectiveness of residential radon safeguards.

1. Introduction

Radon is a ubiquitous radioactive gas in the environment, resulting from the decay of uranium present in the Earth's crust. Radon is released from all types of rocks and soils, its concentration being directly dependent on the amount of radium contained in the various mineral associations of the rocks. Although the primary source of radon is geological, its accumulation inside buildings depends on variables associated with the building itself (Appleton and Miles, 2010; Bossew et al., 2008; Florică et al., 2020; Kemski et al., 2005). Prolonged exposure to high concentrations of radon can lead to the development of lung cancer (Darby et al., 2005; Krewski et al., 2005), with radon being classified as a group 1 carcinogen by the International Agency for Research on Cancer (IARC) (IARC, 1988) and considered the second leading cause of lung cancer after smoking according to the World Health Organization (WHO) (WHO, 2009). These aspects underline the importance of radon monitoring and control in indoor environments.

International regulations, such as Euratom Directive 59/2013, the recommendations of the US Environmental Protection Agency (EPA), and the WHO, also support the need to implement effective mitigation measures. In this context, developing appropriate and effective methods to reduce indoor radon activity concentration (IRAC) has become a priority at the European level, stimulating ongoing research and evaluation in this field.

Radon mitigation methods vary depending on the situation and the characteristics of the building, ranging from natural and mechanical ventilation to crack sealing and soil depressurization systems. Various radon diffusion-resistant membranes are also used to seal floors. Each method has advantages and disadvantages, and their effectiveness can vary significantly depending on the specific characteristics of each site.

Sub-slab depressurization (SSD) is a very popular method known to have the best effectiveness in radon reduction (Holmgren and Arvela, 2012; Khan et al., 2019). This technique involves creating a zone of negative pressure under the foundation slab of a building to trap and redirect radon gas before it enters the indoor environment. The approach is vast, with various technical configurations - from active piping systems to perforated layers under concrete slabs - to achieve this pressure differential. Numerous studies, including those by Naismith (1997) and Steck (2012), have shown that SSD can reduce IRAC by up to 90–95 %. A study confirmed that SSD-based systems can reduce indoor radon by up to 99 %, even in buildings located in areas with very high radon concentrations (Vázquez et al., 2011). Furthermore, an extensive study conducted in the Czech Republic by Jiránek (2014) on 62 dwellings demonstrated that SSD systems achieved average reductions from 1476 Bq/m^3 to 142 Bq/m^3, with efficiencies ranging from 70 % to 98 %, thus reinforcing the reputation of SSD as one of the most reliable and cost-effective remediation techniques. Another effective method is using heat recovery ventilation systems, both centralized (CHRV) and decentralized (DHRV), which introduce fresh air into the building, thereby diluting the IRAC. Although these systems are generally less effective than SSD (Holmgren et al., 2013; Holmgren and Arvela, 2012.; Khan et al., 2019), they can still provide significant radon reduction, especially when combined with other remediation techniques (Groves-Kirkby et al., 2006; Long et al., 2013).

Radon barriers (membranes) are frequently used in new constructions as a preventive measure to reduce radon ingress from the ground. Although in theory they can be an effective barrier against radon gas, their actual effectiveness depends mainly on the quality of the craft, the integrity of the material over time, and the way they are integrated into the structural assembly of the building. The studies reviewed show that, in practice, the use of membranes as the only remedial measure does not guarantee that radon concentrations will be reduced below the recommended thresholds, especially in dwellings with high initial IRAC levels, where the effectiveness of these barriers may be insufficient (Holmgren and Arvela, 2012; Khan et al., 2019). Rahman and Tracy (2009) point out that the installation of membranes during construction did not result in significant reductions in the annual means of IRAC, in contrast to active fan-assisted sump systems, which were found to be the most effective. Also, Baltrocchi et al. (2023) note that membranes used without supplemental ventilation may be insufficient, with some situations where they have failed to limit radon infiltration. Thus, membranes may be helpful in the remediation strategy, but they should not be considered a sole solution, but a complementary component in an integrated radon protection system.

Long-term research indicates that radon remediation procedures are typically durable and consistently successful. In the United Kingdom, a study found that various remediation methods, including SSD and positive ventilation, maintained their effectiveness over five years. The study reported an annual failure rate of only 4 %, mainly attributed to mechanical problems such as fan failures (Naismith, 1997). Similarly, studies conducted in Ireland have demonstrated that active sump systems can attain average reduction efficiencies of up to 92 % (Long et al., 2013). A more recent case study in Spain confirmed this long-term reliability in a public university building, where a forced underfloor ventilation system led to reductions in IRAC between 87 % and 91 %, maintained even three years after implementation (Arias-Ferreiro et al., 2021). These findings support the conclusion that appropriate mitigation strategies can significantly and sustainably lower radon levels within buildings.

The behaviour of building occupants over time is one of the most critical factors that can influence and maintain the effectiveness of remediation at an optimal level over time. Human intervention can impact continuous or intermittent use, system disconnection, or lack of maintenance, leading to increased post-remediation radon concentration, sometimes even above pre-remediation levels. At the same time, pro-active occupant involvement, including constant monitoring and prompt response to faults, becomes the main factor that can ensure the maintenance of low radon levels in a building, long-term after implementation.

Romania has transposed Directive 2013/59/Euratom by adopting several technical and methodological norms, including Government Decision No 528/2018, which lays down the basic requirements for radiological safety and establishes a national reference level for IRAC of 300 Bq/m^3. Where the annual mean of IRAC in a building exceeds this reference level, the competent authorities, in collaboration with other relevant institutions, must establish measures to reduce radon exposure in the premises concerned.

Romania's initiatives to identify regions with elevated radon risk and apply remediation strategies began before the enactment of specific legislation in 2018. These efforts were evident through various international research projects, coordinated by Babeș-Bolyai University of Cluj-Napoca from 2010 to 2024 (Burghele et al., 2021; Cosma et al., 2015). The research projects involved screening over 1500 dwellings, conducting extensive IRAC monitoring campaigns, performing thorough diagnostics for 121 dwellings, implementing remediation works in 31 houses, and ongoing post-remediation measurements. The comprehensive data set from 2012 to 2024 encompasses passive and continuous radon measurements associated with physical parameters. However, in only 10 homes where remediation systems were installed, continuous measurements were taken for over 53 months (November 2019 – March 2024).

The present study aims to assess the long-term effectiveness of the implemented radon mitigation measures based on continuous measurements carried out for 53 months (November 2019–March 2024) and evaluate the occupants' behaviour and adherence to recommended practices concerning radon exposure.

2. Materials and methods

The study focused on ten residential buildings, coded B1 to B10, located in the counties of Bucharest, Cluj, and Timiș, built between 1930 and 2008, with 1951 as the median construction year. All dwellings, except for house B1 which was built with adobe, were primarily constructed using red brick masonry. In terms of thermal insulation, polystyrene was the most used material, while one house (B6) was insulated with mineral wool. Regarding building structure, six houses consist of a single level, two have a ground floor and an upper floor (B8, B10), and the remaining two include a basement, ground floor, and upper floor (B5, B6).

The measurement protocol employed in this study combined both passive (CR-39) and active techniques. The passive method was applied during the pre- and post-mitigation phases, while the active method was used for both the diagnosis campaign and long-term monitoring after remediation. At the end of each exposure period, the CR-39 detectors were processed and analysed at the LiRaCC laboratory using the protocol recommended by the manufacturer (Radosys Ltd., Hungary), as previously described by Burghele et al., 2021. The reliability of the passive radon measurements was supported by the LiRaCC laboratory's successful participation in the proficiency testing exercise for passive radon detectors, organized by the Bundesamt für Strahlenschutz (BfS, Germany).

In addition to these measurements, a detailed diagnosis was performed before remediation using active devices such as AlphaGuard (Bertin SA, France), RadonScout, and RTM (Sarad GmbH, Germany), which are portable instruments capable of real-time radon concentration monitoring and equipped with sensors for temperature, pressure, and humidity. These instruments enabled continuous measurement of radon concentration in both indoor air and soil, as well as assessment of the exhalation rate at the building site. This detailed investigation identified the soil as the primary source of radon in the analysed houses. In parallel, ICA - an original monitoring device developed by our research team within the SMART_RAD_EN project (Tunyagi et al., 2020) - was used for long-term assessment of IRAC, as well as for monitoring indoor air quality parameters such as volatile organic compounds (VOC), carbon monoxide (CO), carbon dioxide (CO_2), and various relevant physical indicators. The ICA device allows continuous data acquisition, with real-time transmission to a cloud-based platform, accessible through both desktop browsers and dedicated mobile applications.

After implementing remediation systems, three-month passive measurements were conducted to evaluate the effectiveness of the measures applied. The results are detailed in Burghele et al. (2021). The present article provides additional information regarding the continuous measurements subsequently carried out over 53 months with the ICA device, which were complemented by one year of parallel passive measurements. Radon concentration was analysed at two scales: room level, referring to measurements taken in individual rooms, and house level, representing aggregated data from all monitored rooms within the same dwelling.

Various mitigation methods were designed and implemented according to the different typology of the selected buildings and addressed to be energy efficient, cost-effective and minimally invasive on the building structure and inhabitants' comfort.

The main applied mitigation systems included sub-slab depressurization (SSD), heat recovery ventilation, both centralized (CHRV) and decentralized (DHRV), and the use of radon barriers.

In some cases, these methods were applied and adapted to the specifics of each building investigated. Burghele et al. (2021) presents more details on the measurement methods and remediation techniques used.

2.1. Questionnaire design and implementation

A structured questionnaire was developed, including 18 items grouped into five thematic sections: (1) perceived utility of the remediation system and ICA device, (2) awareness and effectiveness of automatic system activation, (3) discomfort associated with system operation, (4) energy consumption and perceived cost-benefit balance, and (5) overall satisfaction and long-term sustainability. Each item was rated on a 5-point Likert scale ranging from 1 (Strongly disagree) to 5 (Strongly agree).

Prior to distribution, a short telephone conversation was held with each homeowner to explain the purpose of the questionnaire and obtain verbal consent for participation. The questionnaire was then administered online. Despite these efforts, one of the ten homeowners contacted declined to complete the questionnaire. The data collected complemented long-term quantitative monitoring and provided insight into user experience and system acceptance.

2.2. Statistical analysis

The statistical analysis of the data and the graphical representations were carried out using OriginLab 2024 (OriginLab Corporation, Northampton, MA, USA) software. The robust coefficient of variation (RCV), defined as the ratio of the median absolute deviation (MAD) to the median, was used to assess relative variability in the presence of outliers. Spearman's rank correlation coefficient was used to evaluate the strength of association between variables. A significance level of 0.05 was used.

3. Results

3.1. Long-term post-mitigation measurements

Radon concentration, along with CO_2, CO, VOCs, temperature, pressure, and humidity, was monitored in ten houses using the ICA device for 53 months (November 2019 – March 2024), following the implementation of mitigation solutions. The long-term IRAC values obtained through this method are presented in Table 1 under the label “Active method”. The IRAC results, reported as arithmetic means for the

Table 1
Long-term effectiveness of the implemented remediation solutions in the ten analysed houses, based on room-level measurements.

House code	Mitigation method	IRAC – at room level (Bq/m^3)			Effectiveness (%)[¤]	
		Before remediation[#]	Passive method[*]	Active method[+]	IRAC	CO_2
B1	1 DHRV	459	–	174	62	50
B2	2 CHRV	439	235	219	50	60
B3	2 DHRV	515	294	290	44	19
B4	1 CHRV	662	–	454	31	40
B5	1 DHRV	455	–	490	−8	10
B6	2 DHRV	385	218	174	55	15
B7	1 SSD + 1 DHRV	615	57	54	91	20
B8	1 SSD + Rn membrane	505	42	49	90	–
B9	1 SSD + Rn membrane	737	259	213	71	–
B10	1 SSD + 1 DHRV + Rn membrane	1280	178	234	82	24

[#] *IRAC measured in the room where the ICA device was installed.*
[*] *Thirty-two months after the remediation works.*
[+] *Continuous measurements carried out between November 2019 and March 2024 with ICA device.*
[¤] *Calculated based on active measurements (November 2019–March 2024).*

entire monitored period, reveal substantial variability across the houses, ranging from 49 to 490 Bq/m^3, with an overall mean value of 235 Bq/m^3 and a median of 216 Bq/m^3. Two of the ten monitored houses present IRAC exceeding the reference level, while one additional house is close to this threshold (290 Bq/m^3).

Two and a half years after the remediation solutions were implemented, a monitoring campaign was carried out using passive detectors (CR-39) measuring for one year (June 2022 – July 2023). In three out of the ten analysed homes, the occupants declined the installation of additional detectors. The results obtained from this campaign are shown in Table 1 under the label "Passive method". The Spearman correlation coefficient ($r = 0.94$) computed between active and passive measurements is statistically significant ($p < 0.01$), indicating, on the one hand, the stability over time of the active measurements, and on the other hand, the relevance of passive measurements conducted several years after the installation of mitigation solutions in evaluating its long-term effectiveness.

To evaluate the effectiveness of the remediation solution, the average radon concentration over the entire post-remediation period (53 months) was used and compared to the pre-remediation value explicitly measured in the room where the ICA device had been installed. Accordingly, the calculated remediation effectiveness values ranged from −8 % to 91 %, with a median value of 59 %. Depending on the mitigation method used, CHRV systems show a median efficiency of 41 %, with a range between 31 % and 50 %; DHRV systems have a median of 50 %, with variations between −8 % and 62 %, while SSD-based methods display a median efficiency of 86 %, with a range between 71 % and 91 % (Fig. 1). Very low variability (RCV = 5.2 %) is specific to the SSD method, whereas DHRV shows low variability (RCV = 18 %), and a moderate variability (24 %) is computed for the CHRV method.

In the case of dwellings where a mitigation system equipped with a ventilation component was installed (8 out of the 10 investigated houses), a reduction in CO_2 concentration was also observed compared to the measurements taken during the pre-mitigation campaign. The effectiveness in reducing CO_2 levels showed a median value of 22 %, ranging between 10 % and 60 %. The highest reductions (40 % and 60 %, respectively) were recorded in houses equipped with CHRV-type systems. Fig. 2 illustrates the monthly distribution of CO_2 concentrations before and after installing the CHRV system in house B2. A consistent decrease in CO_2 levels was observed across all months following the implementation of the ventilation-based mitigation system.

3.2. *Comparison of remediation effectiveness with previously published results*

Immediately after the interventions, post-mitigation measurements using a passive method were conducted. The results regarding the effectiveness of the implemented methods, as previously reported by

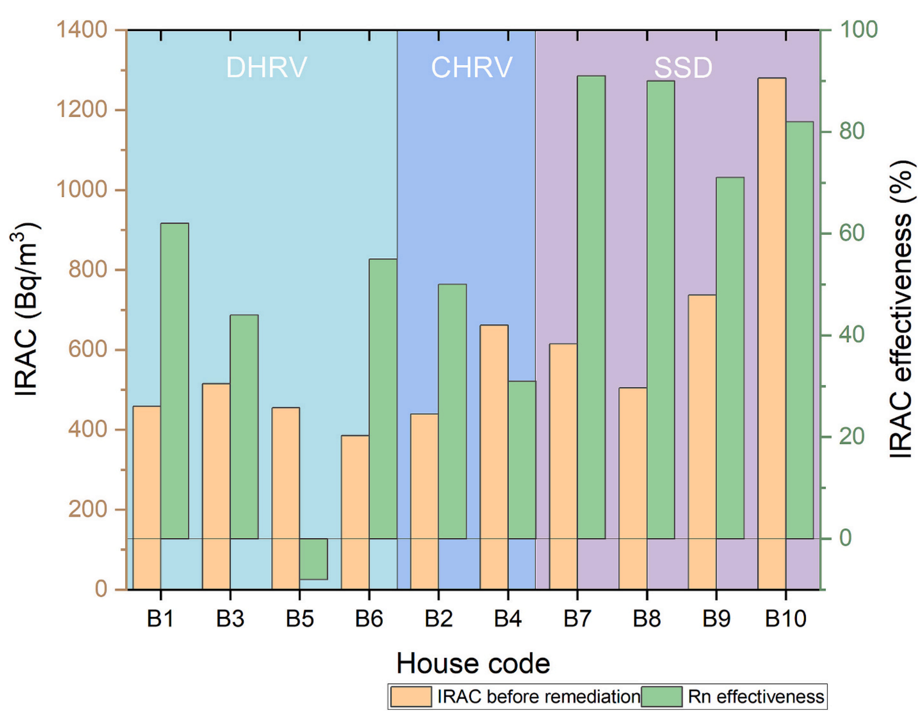

Fig. 1. IRAC before remediation and the effectiveness of the remediation method for the selected rooms.

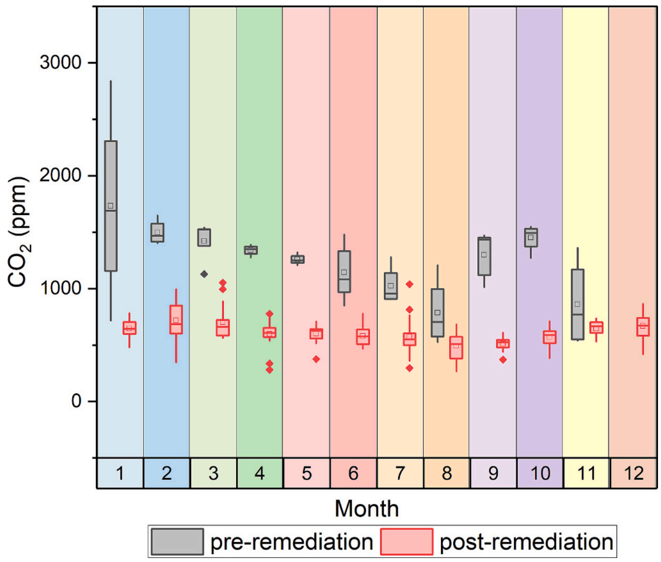

Fig. 2. Monthly variation of indoor CO_2 levels before and after installation of the CHRV system in house B2. The data are represented using boxplots, with grey indicating pre-remediation values (January – November 2019) and red indicating post-remediation values. Post-remediation data integrate monthly CO_2 measurements collected over four years following system installation.

Burghele et al. (2021), are presented in Table 2 under the label "IRAC post mitigation (PM)". Unlike the data presented in Table 1, where effectiveness is calculated relative to the pre-remediation measurements explicitly taken in the room where the ICA device was installed, Burghele et al. (2021) computed effectiveness based on the average radon concentration across the entire household, considering that two rooms were monitored. As a result, the effectiveness values calculated for the long-term post-remediation measurements (IRAC long term) differ from those reported in Table 1. The "IRAC LT–PM" column presents the differences between immediate post-remediation and long-term effectiveness.

The results presented in Table 2 indicate that, although the implemented mitigation methods produced a significant immediate reduction in IRAC (with initial effectiveness ranging from 25 % to 94 % and a median of 66 %), a decline in effectiveness was observed over time in most of the studied buildings. As such, the median difference between short-term and long-term effectiveness (IRAC LT – PM) was −18 %, suggesting that the mitigation performance tends to deteriorate over the years. In extreme cases, such as house B5, the long-term effectiveness was negative (−50 %), while only in two buildings (B6 and B1) the effectiveness showed a positive shift over time (+1 % and + 31 %). The SSD method showed the most stable performance over time, with a median change of −9 % and narrow variability (range: −13 % to −5 %). This supports its reputation as a reliable long-term solution, particularly when properly installed and maintained. These results align with international studies reporting long-term effectiveness typically between 70 % and 95 %. Steck (2012) observed long-term effectiveness averaging about 90 % in Minnesota homes, with 97 % maintaining radon below EPA reference levels several years after remediation. Long et al. (2013) also found sustained effectiveness averaging 91.9 ± 7.5 % in Irish homes remediated by active sumps. Similarly, Synnott et al. (2007) documented that active sump systems in Irish schools maintained high performance (89–97 %) over at least three years without evident performance deterioration. Allison et al. (2008), in a short-term monitoring study in the UK, reported immediate reductions to 18 % (ground floor) and 33 % (first floor) of initial values, confirming substantial initial effectiveness of SSD-type methods, though not directly addressing long-term effectiveness.

Table 2
The effectiveness of the implemented solutions in comparison with those reported by Burghele et al. (2021), based on household-level measurements.

House code	Effectiveness (%)		
	IRAC post mitigation (PM)[#]	IRAC long term (LT)[¤]	IRAC LT - PM
B1	25	56	31
B2	67	49	−18
B3	64	26	−38
B4	64	15	−49
B5	27	−50	−77
B6	54	55	1
B7	92	87	−5
B8	94	87	−7
B9	83	74	−9
B10	94	81	−13

[#] *According to the results presented by Burghele et al. (2021).*
[¤] *Calculated based on active measurements (November 2019–March 2024).*

Instead, DHRV displayed higher variability in long-term effectiveness (median change: −21 %, range: −77 % to +31 %), likely influenced by factors such as occupant compliance, filter maintenance, or mechanical wear. The CHRV method exhibited the steepest decline (median change: −34 %, range: −49 % to −18 %), pointing to potential limitations of the system in maintaining long-term performance without regular servicing. These findings emphasize the sensitivity of ventilation systems, particularly CHRV, to how they are used, their technical configuration, and the consistency of maintenance. Performance can drop considerably if components are not inspected, cleaned, or replaced in due time, or if structural issues such as unsealed openings or lack of duct insulation in unheated spaces are present.

Depending on how they are designed and installed, the efficiency of these types of systems varies significantly, from 30 % to 65 % (Holmgren and Arvela, 2012). In addition, they often require adjustments after installation to operate at optimal parameters. Performance can be further affected in their absence or under challenging conditions, such as low temperatures in the cold season. For example, some systems automatically go into "defrost" mode, temporarily reducing ventilation, allowing radon to accumulate indoors (Groves-Kirkby et al., 2006; Holmgren and Arvela, 2012; Zhou et al., 2021).

The observed temporal variations in remediation effectiveness—ranging from moderate declines to significant efficiency losses—highlight the multifactorial nature of radon dynamics in residential environments. The following section will address the specific causes that may have contributed to these variations for each individual situation.

3.3. Perception and the role of occupant behaviour in remediation system performance

Out of ten homeowners contacted, nine completed the questionnaire evaluating the long-term effectiveness and user experience related to the ICA monitoring device and the radon mitigation systems. Most respondents expressed high levels of satisfaction and trust in the systems' performance, although a few expressed more nuanced or reserved views. Particularly, although the majority agreed that the remediation system had made a substantial contribution to lowering IRAC, one respondent had no opinion on the matter, and another emphasized the difficulty in maintaining system connectivity after some technical modifications.

All nine participants acknowledged the usefulness of ICA monitoring data. However, one respondent expressed only moderate agreement regarding the system's responsiveness when radon thresholds were exceeded. Perceptions of acoustic comfort also varied: three participants reported some degree of discomfort, with one describing the noise as particularly disturbing during colder months, leading to temporary system deactivation. In contrast, others denied any auditory inconvenience. When asked about reducing system use to conserve energy, most respondents (seven out of nine) were opposed, whereas two indicated openness to such compromises.

Most participants indicated a willingness to recommend the mitigation and monitoring systems to others exposed to elevated indoor radon concentrations, reflecting an overall positive evaluation of their experience. However, the presence of occasional technical malfunctions, acoustic discomfort, and variability in system usage patterns highlights the need to accommodate diverse user requirements. These observations emphasize the importance of integrating flexibility, user support mechanisms, and design improvements in the long-term implementation of radon mitigation strategies in residential settings.

Along with the questionnaire-based items, the phone conversations also included targeted follow-up questions aimed at clarifying the temporal variations in IRAC and, consequently, the effectiveness of the mitigation systems.

A significant positive outcome was observed in House B1, where the radon mitigation system remained fully operational despite the house being unoccupied since November 2021. The absence of occupant-related interference allowed the system to function under optimal conditions, resulting in a 31 % improvement in mitigation effectiveness and a 56 % reduction in radon concentration compared to the period immediately following the implementation of the mitigation system (November 2019 – October 2021). This finding highlights the substantial influence of occupancy-related factors, such as ventilation patterns, heat sources, and human activity, on radon dynamics.

In the case of houses B2, B3, and B4, the use of the remediation system was sporadic, influenced by acoustic discomfort and outdoor temperature. The system was switched off or run at lower ventilation capacity during the cold season, when IRAC usually reached their highest levels. This behaviour decreased mitigation effectiveness, ranging from −18 % (B2) to −49 % (B4), compared to the post-mitigation measurements conducted immediately after the system was installed.

The situation in House B5 further emphasized the importance of consistent system use. The system was entirely deactivated shortly after installation due to perceived thermal discomfort. This led to radon concentrations returning to pre-remediation levels (490 Bq/m^3), and a dramatic drop in effectiveness from +27 % to −50 % at the house level. This outcome underscores how occupant non-compliance can ultimately negate technically robust mitigation measures. Similar results were also reported in the study by Prill et al. (1990), where they showed how radon concentrations returned to pre-remediation levels in dwellings where occupants had turned off or incorrectly used remediation systems. On the other hand, Mansour (2021) showed that in most of the analysed houses - more precisely, in 80 % of the cases - radon levels exceeded safe thresholds not because of technical failures of the systems, but simply because they were not correctly checked or maintained. In other words, although the equipment was working, the lack of user involvement completely compromised the effectiveness of remediation.

Conversely, in House B6, consistent and appropriate system operation, supplemented by routine maintenance, ensured stable performance, with only a minor variation of +1 % relative to the initial post-remediation value. This example illustrates that even basic maintenance practices are vital in sustaining radon mitigation outcomes over time.

A particularly illustrative case of proactive user engagement was documented in House B7, where the monitored area was a child's bedroom. Following a fan malfunction, occupants quickly identified elevated radon levels using the ICA monitoring device and responded by reporting the issue and replacing the fan. As a result of this timely intervention, long-term radon concentrations remained low, averaging 54 Bq/m^3. This demonstrates the efficacy of active monitoring and prompt corrective action in preserving system performance (Fig. 3). This pattern of long-term stability has been documented across several other studies. In Steck (2012), SSD systems maintained reductions of over 90 % even after multiple years, with only 3 % of homes exceeding reference levels. Naismith (1997) found annual failure rates under 1 % when occupants were aware and systems were properly installed.

A similar outcome was observed in House B8, where the mitigation system's continuous and uninterrupted operation successfully maintained radon concentrations below 50 Bq/m^3 throughout the monitoring period.

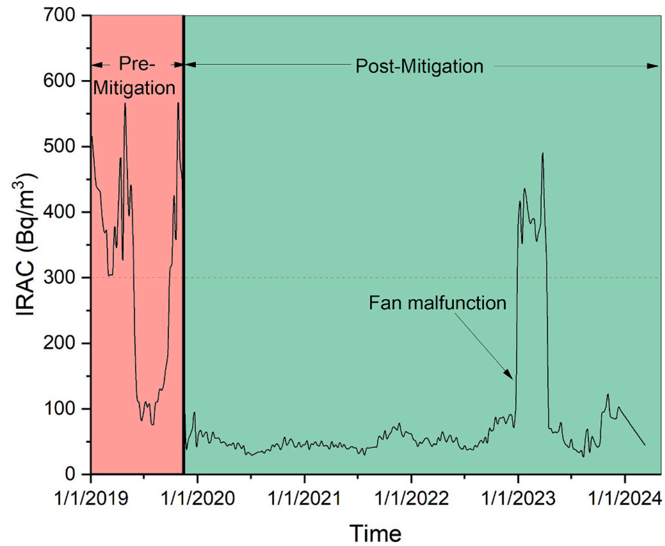

Fig. 3. The temporal variation of IRAC in House B7 highlights the impact of a fan malfunction on post-mitigation performance.

In Houses B9 and B10, occupants employed adaptive usage strategies, such as limiting system operation to daytime hours to reduce energy consumption and minimize noise-related discomfort. Although these modifications resulted in decreased effectiveness from the initial evaluation, the mean radon levels fell below the reference level. These cases suggest that applying specific adjustments to the mitigation remedial system and active monitoring can provide adequate protection against radon exposure.

These findings highlight the critical importance of user engagement and compliance in sustaining the long-term performance of radon mitigation strategies. Even well-designed systems may underperform or fail entirely when consistent usage and maintenance are not ensured.

All these findings are also broadly supported by the findings of recent studies, which, although not directly examining identical situations, provide a relevant conceptual framework for understanding the influence of behaviour on the effectiveness of radon remediation. For example, Hevey et al. (2023) showed that some of those who chose not to take action, although well aware that their home had high radon levels, expressed concern about long-term costs, the maintenance required, and the fact that systems might not work consistently. Even if these fears were expressed before the remediation systems were installed, they can have consequences later, influencing how an intervention is used and maintained over time.

On the other hand, Hevey (2017) draws attention to how people sometimes tend to ignore or avoid information that causes them discomfort, even if they are aware that there is a real risk. This psychological bias can lead to postponed decisions or no action at all. It can even affect interventions that have already started, especially when they require active involvement, such as regular monitoring or maintenance of a remediation system.

In addition, the study by Irvine et al. (2022) provides specific data confirming the impact of behaviour on actual radon exposure. The research shows that only a fraction of those with high radon levels were remediated quickly. Those who delayed or failed to act - mainly for economic reasons - remained exposed to considerable radiation doses. In other words, it is not only the radon level that matters, but also how people react to the risk.

This perspective is also supported by findings from Mansour (2021), whose study in Zone 1 risk areas of the U.S. revealed that 80 % of technically operational mitigation systems failed to keep radon levels below recommended thresholds, not because of design flaws, but due to a complete lack of user involvement in system monitoring and maintenance. The author emphasizes that radon mitigation efforts cannot rely solely on engineering solutions, but must incorporate behavioural components such as education, regular checks, and user responsibility. Our findings reinforce and expand this conclusion by demonstrating that long-term effectiveness is not only dependent upon initial user engagement, but also on sustained behavioural commitment and contextual understanding of the system. This highlights the need for integrated strategies that combine technical robustness with proactive user involvement throughout the lifespan of the mitigation intervention.

4. Conclusion

The results of this study show that user behaviour plays a significant role in the long-term success of radon mitigation systems, in addition to technical performance. Long-term success of mitigation systems requires proper use, routine maintenance, and quick repair when problems occur, even if the systems can maintain low indoor radon concentrations over extended periods. Examples like B6, B7, and B8 highlight the benefits of a proactive and informed approach to system operation, with consistently low radon levels maintained through continuous engagement with monitoring data and adherence to maintenance protocols. On the other hand, intermittent use, system shutdowns, and lack of maintenance, motivated by factors such as thermal or acoustic discomfort, caused significant effectiveness losses and, in some instances, an elimination of mitigation effectiveness. These results underscore the need to view radon mitigation as a dynamic, user-influenced process rather than a one-time technical intervention.

Although different remediation strategies were implemented in the ten case studies, sub-slab depressurization (SSD) based systems were the most stable and efficient over time, with a median efficiency of 86 % and very low variability. In contrast, decentralized heat recovery ventilation (DHRV) and centralized heat recovery ventilation (CHRV) systems exhibited considerably higher variability and, in some cases, a sharp decline in performance, highlighting the increased sensitivity of these systems to maintenance and user compliance. In extreme cases, such as dwelling B5, the remediation efficiency dropped from +27 % to −50 % due to the complete deactivation of the system shortly after installation. In contrast, homes with SSD systems maintained radon concentrations well below the reference level (often below 50 Bq/m^3) for more than four years of continuous monitoring.

The study also highlights the crucial need to use effective radon remediation strategies in buildings to protect public health and occupant comfort, but with the condition of ensuring their proactive cooperation to maintain the reduction of high radon concentrations over time.

At the public health and policy level, these findings affirm the significance of user education, easy-access monitoring devices, and support systems that promote long-term compliance and system maintenance. The first key steps to ensuring the long-term effectiveness of radon reduction initiatives in dwellings are providing users with real-time data and emphasizing the role of human behaviour in sustaining air quality improvements.

CRediT authorship contribution statement

Ștefan Florică: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Alexandru Lupulescu:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Tiberius Dicu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ancuta Tenter:** Investigation. **Gabriel Dobrei:** Investigation. **Mircea Claudiu Moldovan:** Investigation. **Bety Burghele:** Investigation. **Kinga Hening:** Investigation. **Istvan Pap:** Investigation. **Şerban Grecu:** Investigation, Data curation. **Marius Botoș:** Software, Data curation. **Raluca Ciur:** Investigation. **Carlos Sainz:** Writing – review & editing, Project administration, Investigation. **Carmela Carpentieri:** Writing – review & editing. **Christian Di Carlo:** Writing – review & editing. **Alexandra Laura Cucoș:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation.

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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.scitotenv.2025.179962.

Data availability

Data will be made available on request.

References

Allison, C.C., Denman, A.R., Groves-Kirkby, C.J., Phillips, P.S., Tornberg, R., 2008. Radon remediation of a two-storey UK dwelling by active sub-slab depressurisation: effects and health implications of radon concentration distributions. Environ. Int. 34, 1006–1015. https://doi.org/10.1016/j.envint.2008.03.007.

Appleton, J.D., Miles, J.C.H., 2010. A statistical evaluation of the geogenic controls on indoor radon concentrations and radon risk. J. Environ. Radioact. 101, 799–803. https://doi.org/10.1016/j.jenvrad.2009.06.002.

Arias-Ferreiro, G., Otero-Pazos, A., Ares-Pernas, A., Fernández-Ibáez, I., Rodríguez-Gómez, B.A., Calvo-Rolle, J.L., 2021. Study, measurement and mitigation of radon activity concentration in the School of Computer Science of a Coruña in the north west of Spain. J. Radiol. Prot. 41. https://doi.org/10.1088/1361-6498/abe170.

Baltrocchi, A.P.D., Maggi, L., Dal Lago, B., Torretta, V., Szabó, M., Nasirov, M., Kabilov, E., Rada, E.C., 2023. Mechanisms of diffusion of radon in buildings and mitigation techniques. Sustainability 16, 324. https://doi.org/10.3390/su16010324.

Bossew, P., Dubois, G., Tollefsen, T., 2008. Investigations on indoor radon in Austria, part 2: geological classes as categorical external drift for spatial modelling of the radon potential. J. Environ. Radioact. 99, 81–97. https://doi.org/10.1016/j.jenvrad.2007.06.013.

Burghele, B.D., Botoş, M., Beldean-Galea, S., Cucoş, A., Catalina, T., Dicu, T., Dobrei, G., Florică, Ş., Istrate, A., Lupulescu, A., Moldovan, M., Niţă, D., Papp, B., Pap, I., Szacsvai, K., Sainz, C., Tunyagi, A., Ţenter, A., 2021. Comprehensive survey on radon mitigation and indoor air quality in energy efficient buildings from Romania. Sci. Total Environ. 751, 141858. https://doi.org/10.1016/j.scitotenv.2020.141858.

Cosma, C., Papp, B., Cucoş Dinu, A., Sainz, C., 2015. Testing radon mitigation techniques in a pilot house from Băiţa-Ştei radon prone area (Romania). J. Environ. Radioact. 140, 141–147. https://doi.org/10.1016/j.jenvrad.2014.11.007.

Darby, S., Hill, D., Auvinen, A., Barros-Dios, J.M., Baysson, H., Bochicchio, F., Deo, H., Falk, R., Forastiere, F., Hakama, M., Heid, I., Kreienbrock, L., Kreuzer, M., Lagarde, F., Mäkeläinen, I., Muirhead, C., Oberaigner, W., Pershagen, G., Ruano-Ravina, A., Ruosteenoja, E., Rosario, A.S., Tirmarche, M., Tomáscaron;ek, L., Whitley, E., Wichmann, H.-E., Doll, R., 2005. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. BMJ 330, 223. https://doi.org/10.1136/bmj.38308.477650.63.

Florică, Ş., Burghele, B.D., Bican-Brişan, N., Begy, R., Codrea, V., Cucoş, A., Catalina, T., Dicu, T., Dobrei, G., Istrate, A., Lupulescu, A., Moldovan, M., Niţă, D., Papp, B., Pap, I., Szacsvai, K., Ţenter, A., Sferle, T., Sainz, C., 2020. The path from geology to indoor radon. Environ. Geochem. Health 42, 2655–2665. https://doi.org/10.1007/s10653-019-00496-z.

Groves-Kirkby, C.J., Denman, A.R., Phillips, P.S., Crockett, R.G.M., Woolridge, A.C., Tornberg, R., 2006. Radon mitigation in domestic properties and its health implications—a comparison between during-construction and post-construction radon reduction. Environ. Int. 32, 435–443. https://doi.org/10.1016/j.envint.2005.10.004.

Hevey, D., 2017. Radon risk and remediation: a psychological perspective. Front. Public Health 5. https://doi.org/10.3389/fpubh.2017.00063.

Hevey, D., Perko, T., Martell, M., Bradley, G., Apers, S., Rovenská, K.N., 2023. A psycho-social-environmental lens on radon air pollutant: authorities', mitigation contractors', and residents' perceptions of barriers and facilitators to domestic radon mitigation. Front. Public Health 11. https://doi.org/10.3389/fpubh.2023.1252804.

Holmgren, O., Arvela, H., 2012. STUK-A251 / MARCH 2012 Säteilyturvakeskus Strålsäkerhetscentralen Radiation and Nuclear Safety Authority a Assessment of Current Techniques Used for Reduction of Indoor Radon Concentration in Existing and New Houses in European Countries.

Holmgren, O., Arvela, H., Collignan, B., Jiránek, M., Ringer, W., 2013. Radon remediation and prevention status in 23 European countries. Radiat. Prot. Dosim. 157, 392–396. https://doi.org/10.1093/rpd/nct156.

IARC, 1988. Monographs on the Evaluation of the Carcinogenic Risks to Humans.

Irvine, J.L., Simms, J.A., Cholowsky, N.L., Pearson, D.D., Peters, C.E., Carlson, L.E., Goodarzi, A.A., 2022. Social factors and behavioural reactions to radon test outcomes underlie differences in radiation exposure dose, independent of household radon level. Sci. Rep. 12. https://doi.org/10.1038/s41598-022-19499-5.

Jiránek, M., 2014. Sub-slab depressurisation systems used in the Czech Republic and verification of their efficiency. Radiat. Prot. Dosim. 162, 64–67. https://doi.org/10.1093/rpd/ncu219.

Kemski, J., Klingel, R., Siehl, A., Stegemann, R., 2005. Radon transfer from ground to houses and prediction of indoor radon in Germany based on geological information. Radioactivity in the Environment 7, 820–832. https://doi.org/10.1016/S1569-4860(04)07103-7.

Khan, S.M., Gomes, J., Krewski, D.R., 2019. Radon interventions around the globe: a systematic review. Heliyon 5, e01737. https://doi.org/10.1016/j.heliyon.2019.e01737.

Krewski, D., Lubin, J.H., Zielinski, J.M., Alavanja, M., Catalan, V.S., Field, R.W., Klotz, J. B., Létourneau, E.G., Lynch, C.F., Lyon, J.I., Sandler, D.P., Schoenberg, J.B., Steck, D. J., Stolwijk, J.A., Weinberg, C., Wilcox, H.B., 2005. Residential radon and risk of lung Cancer. Epidemiology 16, 137–145. https://doi.org/10.1097/01.ede.0000152522.80261.e3.

Long, S., Fenton, D., Cremin, M., Morgan, A., 2013. The effectiveness of radon preventive and remedial measures in Irish homes. J. Radiol. Prot. 33, 141–149. https://doi.org/10.1088/0952-4746/33/1/141.

Mansour, O.E., 2021. Re-examining the efficacy of radon mitigation Systems in Single-Family Dwellings: a pilot study. Zero Energy Mass Custom Home ZEMCH International Conference 626–647.

Naismith, S., 1997. DURABILITY OF RADON REMEDIAL ACTIONS. Nuclear Technology Publishing, Radiation Protection Dosimetry TECHNICAL NOTE.

Prill, R.J., Fisk, W.J., Turk, B.H., 1990. Evaluation of radon mitigation systems in 14 houses over a two-year period. J. Air Waste Manage. Assoc. 40, 740–746. https://doi.org/10.1080/10473289.1990.10466719.

Rahman, N.M., Tracy, B.L., 2009. Radon control systems in existing and new construction: a review. Radiat. Prot. Dosim. 135, 243–255. https://doi.org/10.1093/rpd/ncp112.

Steck, D.J., 2012. The effectiveness of mitigation for reducing radon risk in single-family Minnesota homes. Health Phys. 103, 241–248. https://doi.org/10.1097/HP.0b013e318250c37a.

Synnott, H., Colgan, P.A., Hanley, O., Fenton, D., 2007. The effectiveness of radon remediation in IRISH schools. Health Phys. 92, 50–57. https://doi.org/10.1097/01.HP.0000234038.25522.98.

Tunyagi, A., Dicu, T., Cucos, A., Burghele, B., Dobrei, G., Lupulescu, A., Moldovan, M., Niță, D., Papp, B., Pap, I., Szacsvai, K., Ţenter, A., Beldean-galea, M., Anton, M., Grecu, Ş., Cioloca, L., Milos, R., Botos, M., Chiorean, C.G., Catalina, T., Istrate, M.A., Sainz, C., 2020. An innovative system for monitoring radon and indoor air quality. Rom. J. Physiol. 65 (803), 1–14.

Vázquez, B.F., Adán, M.O., Quindós Poncela, L.S., Fernandez, C.S., Merino, I.F., 2011. Experimental study of effectiveness of four radon mitigation solutions, based on underground depressurization, tested in prototype housing built in a high radon area in Spain. J. Environ. Radioact. 102, 378–385. https://doi.org/10.1016/j.jenvrad.2011.02.006.

World Health Organization, 2009. WHO handbook on indoor radon: a public health perspective. World Health Organization.

Zhou, L. (Grace), Berquist, J., Li, Y. (Ethan), Whyte, J., Gaskin, J., Vuotari, M., Nong, G., 2021. Passive soil depressurization in Canadian homes for radon control. Build. Environ. 188, 107487. https://doi.org/10.1016/j.buildenv.2020.107487.