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Comprehensive survey on radon mitigation and indoor air quality in energy efficient buildings from Romania

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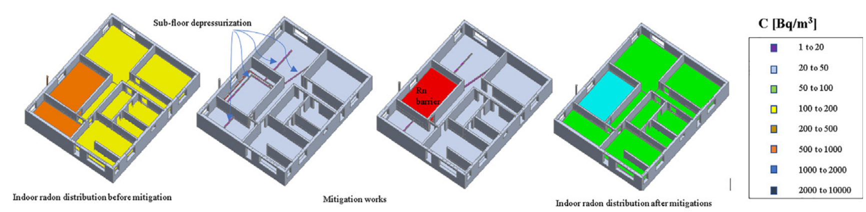
HIGHLIGHTS

- High indoor radon levels are not specific to radon priority areas.
- Retrofit works should include mandatory radon survey and mechanical ventilation.
- SSD combined with radon barrier yields the highest efficiency in radon reduction.
- Indoor air quality mitigation requires indoor heat recovery ventilation.
- Mitigations of inhabited buildings can be inconvenient yet highly beneficial.

GRAPHICAL ABSTRACT



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ABSTRACT

Over the last 10 years applied scientific research has been carried out in Romania to tacked the residential radon issues. The increased interest to reduce the carbon footprint of buildings has lead to the implementation and use of new architectural solutions aimed to save energy in houses and other buildings. As a consequence, the degree of retrofit in existing buildings and energy efficiency of new buildings promoted the need to not only mitigate indoor radon, but improve indoor air quality overall. The present study found that the while the best performance in radon reduction was confirmed to be based on sub-slab depressurization (61% - 95% reduction), centralized and decentralized mechanical supply and exhaust ventilation with heat recovery yielded a good efficiency in overall improvement of indoor air quality (CO_2, VOC, RH, temperature). The outcome of our research, as well as future perspectives, take into account the recommended harmonization of energy efficiency programs with those of public health by finding and applying the best technologies in compliance with energy saving and indoor environmental quality.

1. Introduction

Radon is one of the most important air pollutants. Found in trace concentrations outdoors (between 5 and 15 Bqm^{-3}) it can accumulate

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to life threatening concentrations when trapped indoors (WHO, 2016). Radon accumulation indoors is dependent both on natural conditions (geogenic radon, soil properties) as well as anthropogenic factors, such as construction and current condition of a building which can allow radon to migrate from the ground through various opened pathways into the living spaces (Cosma et al., 2013a; Dai et al., 2019; Florică et al., 2020). Epidemiological studies have established that exposure to enhanced levels of radon can lead to life-threatening diseases, particularly lung cancer (Darby et al., 2005; WHO, 2018). Specialized international organizations identified radon as a category one human carcinogen (IARC, 1988; ICRP, 2007; WHO, 2009). On the other hand, radon is a modifiable cause of lung cancer.

Several mitigative actions, by which indoor radon concentrations can be cost-effectively reduced, have been developed and implemented worldwide, in order to lower the associated health risk (Khan et al., 2019). The techniques can be divided into two main categories: those focusing on the treatment of a contaminated indoor environment and those intended to prevent radon rich soil gas from entering the living areas. The choice of an adequate mitigation technique should always be made individually and since the effectiveness of radon interventions cannot be predicted a priori, confirmatory tests should be performed to certify that the radon exposure has been reduced to at least bellow the regulated levels (Euratom, 2014; HG nr526, 2018). The cost-effectiveness in health terms of radon mitigation for residential buildings has been extensively validated (Haucke, 2010; Gaskin et al., 2019).

One novel aspect in the fight against radon exposure is the home-engineering practices focused on energy efficiency which has been associated with low air exchange rates and increased indoor radon levels (Milner et al., 2014; Cucoş et al., 2015; Stanley et al., 2017; Pampuri et al., 2018; Collignan and Powaga, 2019). Airtightness of buildings has been negatively linked to not only indoor radon but also to other indoor air quality indicators (Du et al., 2019). In the wake of increasing demand for building retrofit and based on the most recent published data indicating that a high percentage of buildings already register elevated indoor radon (Cucoş (Dinu et al., 2017) the Romanian government has started to control the effects of indoor air pollution by issuing a standard to limit, through mitigations, indoor radon concentration to 300 Bqm^{-3} (HG nr526, 2018).

Given the paramount importance of radon mitigation in the quest for healthier living, the Babeş-Bolyai radon research group has solely undertaken the task of mitigating various levels of indoor radon in residential buildings of representative architecture, occupancy and environmental setting in Romania. The present paper discusses the applicability of different mitigative actions from a scientific perspective. The objective of this research was to raise public and stakeholder awareness on the necessity of implementing comprehensive mitigation, focusing not only on radon or radon priority areas, but coherently addressing the indoor air quality spectrum.

2. Materials and methods

2.1. Site description

Two specific sites and a total of 30 individual buildings were considered for the present research study. The most common characteristic of the building sites was the high radon potential, identified in previous works (Cosma et al., 2013b; Burghele et al., 2019; Floricǎ et al., 2020). As recommended by Groves-Kirkby et al. (2006), all residences considered have been occupied for several years prior to the present study, thus the dissipative/diffusive effect of normal daily living, including the use of heating has been averted. A second common characteristic of the residential buildings selected for radon mitigation was the retrofit works undertaken during the recent years, such as double-glazed windows, indoor or outdoor thermal insulation, yet without additional mechanical ventilation. The lack of mechanical ventilation has been observed in other energy efficient buildings, in association with elevated indoor radon concentrations (Sferle et al., 2020). Kotol et al. (2014) observed that although the thermal and noise comfort is enhanced in energy efficient buildings, ventilation by opening windows could lower the gain by creating humidity issues and introducing outdoor pollutants.

The first research site is located in the countryside of Bihor County, protected by the clear air of the Bihor Mountains and is comprised of four localities: Băiţa, Nucet, Fînaţe and Cîmpani. From a radon perspective, the site overlaps a radon priority area (Sainz et al., 2009; Cucoş et al., 2012; Dicu et al., 2019), distributed along the banks of a small river coming down through the former uranium mining site of Băiţa Plai (Begy et al., 2012). Overall, 20 residential buildings were selected (hereafter reported as batch A), based on voluntary registration, for experimental radon mitigation. This set of dwellings had a particular characteristic, the building material, which was partially made of by-products of uranium mining operations (Cosma et al., 2013a).

The second site selected for mitigative works was represented by the metropolitan areas of three major cities of Romania (Cluj-Napoca, Timişoara, Bucharest) where, additionally to indoor radon risk (Todea et al., 2013), the outdoor pollution often exceeds the recommended threshold (IQAir, 2019). Ten buildings (hereafter reported as batch B), selected among those representative for each region's architecture have been selected for indoor air quality mitigation.

2.2. Measurements

In a first stage, all houses selected for the study were passively monitored using solid state nuclear track detectors (RSKS, Radosys Ltd. Hungary). Detectors were installed in one to three rooms, selected based on inhabited volume and the highest occupancy factor, following the nationally recommended methodology (Decree185, 2019). Each detector was placed and recovered by trained researchers, ensuring suitable locations and accurate exposure duration.

The second stage of measurements required a detailed radon diagnostic of each building site, i.e. indoor and outdoor. Information about the building characteristics and conditions collected from the inhabitants by a questionnaire included: dimension and volume, energy usage, building materials, retrofit works, presence of screed or cellar, type of heating and ventilation system, how the owners perceive the indoor environmental quality, health status, renovation history, etc. Additionally, the following qualitative and quantitative aspects were investigated by the researchers: building tightness, geology, soil permeability, indoor radon mapping, indoor chemical cocktail, radon index of the building site, gamma dose measurements of soil and building materials, etc. Each building's airtightness level was determined using floors/walls exhalation measurements, detection of relevant radon leakages by grab sampling, identification of air flows movements by air flow test tubes and thermography cameras and rate of indoor CO_2 dispersion. The general working protocol has been described in previous works (Barnet et al., 2008; Cosma et al., 2015; Floricǎ et al., 2020). An indoor air quality monitoring system named ICA, was developed by the Babeş-Bolyai research group (Tunyagi et al., 2020) and installed in house B1-B10 to record real-time properties (temperature (T), atmospheric pressure (p), relative humidity (RH), carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOC) and radon (^{222}Rn)) of the household environment for up to one year prior to mitigation works and continuously recorded data ever since.

Follow-up measurements were carried out to verify the effectiveness of mitigation measures implemented in order to reduce radon exposure and optimize occupant protection, in accordance with national methodology (Decree185, 2019). All follow-up measurements were performed during corresponding season as pre-mitigation measuring campaigns, in order to reduce bias cause by temporal variability. During this final test the houses were occupied and the indoor heating was normally operating in order to simulate the air-flow anticipated.

All instrumentation used belong to the Constantin Cosma Radon Laboratory, nationally designated radon laboratory by the National Commission for Nuclear Activities Control, in accordance with ISO/IEC 170252.

2.3. Mitigation

Considering the different typology of the selected buildings, customized and individually dedicated mitigative actions had to be drawn up in order to meet the needs for health and comfort of residents. The mitigation plans were designed by an interdisciplinary research group composed of radon experts, civil building engineers and ventilation system engineers. Each particular system was meant to be innovative, energy efficient, cost-effective and minimally invasive on the building structure and inhabitants' comfort. The mitigation works included techniques based on depressurization of the building sub-slab (SSD), radon barrier, fan-assisted sump, simple ventilation and heat recovery ventilation. The mitigation systems installed in houses B1–B10 included a real time indoor monitoring ICA system which would enable the mechanical ventilation when/if a pre-set threshold of indoor pollutants is exceeded. The main solutions used to reduce radon concentrations in Romanian dwellings are being described in the following sub-chapters.

2.3.1. Mechanical sub-slab depressurization system (MSSDS)

Flexible and perforated polyvinyl chloride (PVC) vent pipes (diameter of 100 mm) were placed into a permeable layer underneath the flooring. In order to maintain a low impact on the house structure and its inhabitants, the vent pipes were inserted by drilling under the existent floor of targeted rooms from outside the building or from the cellar. Whenever this option was not applicable, the mitigation works resumed to disturbing only one room from which a network of vent pipes was created, to cover as many surrounding rooms as possible. If the footprint of the building was too large for only one ventilator, additional measures were resorted to. All flexible vent pipes were connected to an airtight PVC duct, provided, at the outdoor end, with an exhaust fan. Special care was given to the tilting of the airtight ducts in order to avoid the accumulation of condensed soil water vapors. Air containing radon was extracted through these piping networks and exhausted outdoors, away from windows and doors, before it could breach the flooring layer and accumulate inside the living spaces.

2.3.2. Mechanical sump depressurization system (MSDS)

To limit the impact on living spaces a radon sump was created in the cellar or outside the foundation wall, whenever the architecture allowed it. In order to be eligible for this mitigation technique, the house had to have a shallow foundation or a cellar with direct access from within the house. These deep radon extractors were perforated PVC pipes (Φ 400 mm, 80 cm in length) buried in a thin layer of gravel to facilitate the extraction of radon from the surrounding environment. The sump was left hallow and covered with a PVC top. An airtight pipe, equipped with an electric fan, was attached to the top of the sump and guided above the roof where it ended with a wind turbine.

2.3.3. Centralized heat recovery ventilation system (CHRV)

In those houses where the floors had a concrete slab, the mitigation works were oriented towards the indoor environment. The indoor air quality was controlled through mechanical ventilation balanced with heat recovery, equipped with heat inverter that introduces fresh air into the living rooms and bedrooms and exhaust polluted air through the bathroom or kitchen. The solution includes chalking of radon entry points identified during the building's detailed diagnostic.

2.3.4. Decentralized heat recovery ventilation system (DHRV)

The fastest and least invasive mitigation method was used in two houses where inhabitants accepted interventions of small duration and only in the rooms with the highest radon readings. The mitigation solution involved balanced mechanical ventilation with a heat inverter that introduces fresh air into living areas and removes it through the same path. The polluted indoor air was evacuated to the outside environment, giving off heat to the fresh air that was introduced from outside. The heat transfer was achieved through a double copper heat exchanger (without direct intersection of air flows). The inlet/outlet air flow is done with the help of air grilles. The solution includes chalking of radon entry points identified during the building's detailed diagnostic.

Methods based on MSSDS and MSDS require information about the radon concentration and permeability of the soil in which it was to be installed. These are applicable to all radon concentrations, given the building's architecture allows it.

On the other hand, methods based on CHRV and DHRV are recommended when rooms are provided with a radon-impermeable interface on contact with the soil, such as a screed or concrete slab that often has a low radon diffusion. Methods based on indoor air exchange are limited by the fan's ability to remove radon before it can accumulate. This type of ventilation cannot be obtained without thermal discomfort and elevated energy consumption. Therefore, methods based on increased indoor ventilation are only recommended for medium and low radon concentrations.

The efficiency of the radon reduction system has been assessed based on radon concentrations, measured with passive detectors, before (C_1) and after (C_2) intervention in various rooms of the house and reported as house average, using the following equation:

$$Efficiciency\ (\%) = \frac{C_1 - C_2}{C_1} \times 100\%$$

3. Results

3.1. Pre-mitigation measurements

The first set of passive results was obtained in 2010 based on two sets of consecutive measurements covering a full year. The annual indoor radon concentration for batch A (radon priority area) prior to mitigation was 992 Bqm^{-3} with house values ranging from 530 Bqm^{-3} to 2135 Bqm^{-3}. The geometric mean and geometric standard deviation were 912 Bqm^{-3} respectively 1.50 Bqm^{-3}. The second survey began in 2016 with biannual sampling followed by seasonal sampling. The annual indoor radon concentration for batch B (metropolitan areas) prior to mitigation was 529 Bqm^{-3} with house values ranging from 326 Bqm^{-3} to 1221 Bqm^{-3}. The geometric mean and geometric standard deviation were 483 Bqm^{-3} respectively 1.51 Bqm^{-3}. Individual results have been listed in Table S1 of Supplement 1.

3.2. Building inspection

Following the detailed measurements, and according to the classification drafted by Neznal et al. (2004), it was established that the permeability of the building sites was unanimously *high* for batch A, while it covered the full spectrum in case of batch B. This natural characteristic of the building site can determine the applicability of certain mitigation measures, such as sub-slab depressurization, its efficiency being directly corelated with the permeability of the sub-slab layer. The third quartile of radon concentration at 0.8 m below the surrounding building sites was found to vary between 6.1 kBqm^{-3} and 82 kBqm^{-3}. Similar to the results published by Florică et al. (2020), the radon in soil values could not be directly correlated to indoor levels. 60% of the houses involved in radon mitigation were provided with an uninhabitable, small cellar (under one, maximum two rooms), yet with direct access to the interior of the house in half of the cases. The majority of the buildings (87%) were constructed with red bricks and were retrofitted with double-glazed windows (90%). Another common feature (87%) was the presence of opened staircases to upper floors and/or a chimney stack. All these construction features, often combined with a non-thermally insulated wooden ceiling, guaranteed the stack effect which lead to the accumulation of indoor radon above the levels expected based solely on the concentration of radon in soil. Building radon mapping revealed horizontal and vertical variability of indoor radon, one example of such behavior being represented in Fig. 1.

Seasonal, weekly and daily variability was observed for indoor air pollutants such as radon, CO_2 and RH with higher levels recorded during the night hours of the cold season. The average indoor temperature during the heated season was within national recommendations of 20 °C to 27 °C (Regulation22/06/2011, n.d.) in all investigated houses. The CO_2 concentration recorded in 10 houses was comparable to other values reported for energy efficient residential buildings in Romania (Sferle et al., 2020). Based on indoor CO_2 concentration, the Romanian regulations (Regulation22/06/2011, n.d.) divides the indoor air quality into 4 categories (high, average, moderate and low). Following this classification, only 3 houses can be reported as having CO_2 levels in the category of high indoor air quality. On the other hand, in these same 3 houses, radon values between 230 Bqm^{-3} and 874 Bqm^{-3} were registered, the average per house being always above 300 Bqm^{-3}. Total VOC readings showed concentrations between 24% and 86% with frequent exceedances of the upper limit of detection (100%) in those periods when the inhabitants were at home, which suggests that their source is represented by personal care and cleaning products.

Table 1
Different mitigation solutions implemented post-construction.

Main system	Additional measures	Efficiency/house (%)
Sub-slab depressurization	Rn barrier membrane + wind turbine	61–95
	Rn barrier membrane + outdoor sump + wind turbine	88–92
	Rn barrier membrane	76–95
	Rn barrier membrane + cellar sump + wind turbine	78
	Rn barrier membrane + decentralized heat recovery ventilation	94
	Outdoor sump + wind turbine	82
	Wind turbine	72
	Decentralized heat recovery ventilation	92
Sump depressurization	Wind turbine	78
	Rn barrier membrane + wind turbine	85
	Rn barrier membrane + wind turbine + mechanical exhaust ventilation of the cellar	73
Centralized heat recovery ventilation	2 units + mechanical exhaust ventilation of the cellar	67
	1 unit	64
Decentralized heat recovery ventilation	1 unit	25–27
	2 units	54–64

3.3. Mitigation works

The experimental study on radon mitigations conducted in Romania evaluated four main techniques in combination with 14 additional measure. Table 1 shows the effectiveness of each radon mitigation solution, implemented in Romania since 2012, in two different research studies (*IRART* and *SmartRadEn*).

The best performance in radon reduction was recorded in those houses were the main mitigation technique was based on sub-slab depressurization (61% - 95% reduction) followed by underground sump depressurization (73% - 85% reduction). As a general rule, the SSD system was assisted by radon barrier membrane (Monarflex – BMI group, Romania), with three exceptions, when the interventions were conducted from outside the building. Radon reduction efficiency reached only up to 92% when the radon membrane was absent. Sub-slab depressurization systems were designed to serve between one and three rooms, as needed, yet considering the least disturbance of the living spaces. This task was achieved by drilling – and inserting perforated pipes under the target slabs – from outside the building or from only one room located inside the house. Fig. 2 presents a graphical representation of a sub-slab depressurization system implemented in one of the studied buildings.

The reduction capacity of underground sumps was assessed in two locations, i.e. underneath the basement slab and outside the foundation wall, each fitted with an evacuation pipe running to above roof level. A detailed representation of the underground sump has been published by (Cosma et al., 2015). Similar to results reported in Spain (Vázquez et al., 2011), the underground sump positioned outside the foundation wall yielded a good efficiency in radon reduction, due to the

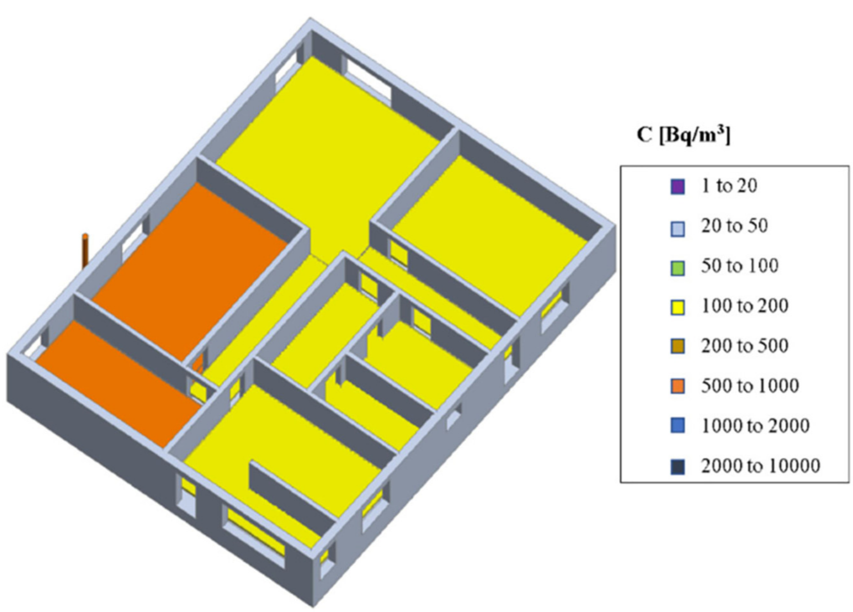

Fig. 1. Horizontal distribution of indoor radon in a detached house (B9).

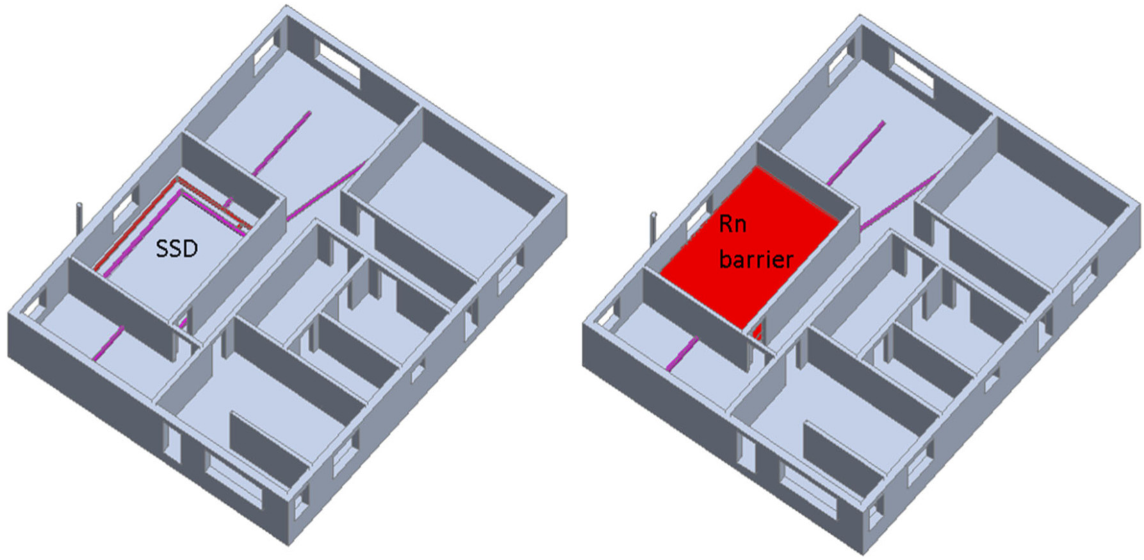

Fig. 2. Post-construction implementation of a sub-slab depressurization system combined with radon barrier (B9).

combination of great depth of sump and shallow foundation, which allowed and efficient extraction of radon from under the building. The position of the ventilator and exhaust pipe was determined by the available options, i.e. bathroom, attic, outside wall or front yard garden.

Whenever the exhaust pipe could be installed above the roof level (20 houses), it was equipped with a wind turbine. The study conducted on a pilot hose by Cosma et al., (2015) pointed out that the use of wind turbines in radon mitigation is not always justified, its operational being directly dependent on meteorological parameters. In the present study, however, the indoor radon concentration decreased following the installation of wind turbines in 80% of homes of batch A. The use of wind turbines is to be encouraged, whenever applicable, due to its low energy impact. Centralized and decentralized mechanical supply and exhaust ventilation with heat recovery yielded the lowest efficiency in radon reduction (25% - 67% reduction) yet it proved a good efficiency in overall improvement of indoor air quality (CO_2, VOC, RH, temperature). Correlations were observed between the indoor radon concentration and outdoor meteorological conditions based on ICA real-time monitoring. Although seasonal variability was clearly established prior to mitigation, the changes in pressure induced by variations in the indoor-outdoor temperature gradients had no effect on the indoor radon levels after mitigation, as it can be observed in Fig. 3.

The effectiveness of the mitigation works could not be corelated to the season in which they took place, i.e. during the summer for batch A and late autumn for batch B.

3.4. Post-mitigation measurements

Active and passive monitoring devices were installed in each house shortly after the mitigation works have been completed. The active real-time monitoring, installed in batch B, recorded the changes of indoor radon before, during and after mitigation works. Fig. 4 presents the variation in time of radon in house B7, under different stages of mitigation. Initial house conditions were as follows: wooden floor on exposed soil, double-glazed windows, natural ventilation.

The installation of DHRV yielded a notable improvement of the indoor air quality, in terms of CO_2 concentration, yet the radon levels did not decrease below the cost-effectiveness threshold of 100 Bqm^{-3} suggested by (Haucke, 2010). In a second stage of mitigations works, a minimally invasive SSD system was installed under the wooden floor, by means of a perforated pipe drilled in from outside the building. In the absence of a concrete slab, the wooden floor proved sufficient in creating and maintaining the sub-floor negative pressure required in order to prevent radon entering indoors. The indoor air quality was generally and cost-effectively improved by combining and implementing these two mitigations techniques in two houses (B7 and B10). On the other hand, this observation also pointed out that using these two techniques separately could hardly bring about the same outcome, as it can be observed in Table 2.

The CO_2 concentration, often an indicator of indoor air quality (Lazović et al., 2016), decreased in all investigated environments, the Romanian standard of high indoor air quality being achieved in 70% of cases. Other indoor air quality parameters recorded for batch B, such as temperature and RH, did not require corrections and were maintained post-mitigation within recommendations, i.e. 20–27 °C, respectively 30–70% (Regulation22/06/2011, n.d.). The VOC readings after the implementation of mitigation systems decreased to concentrations between 14% and 70%, for similar winter months. Individual results on indoor air quality have been listed in Table S2 of Supplement 1.

At the time of the first mitigation works (batch A), Romanian legislation did not include radon as a risk factor. Therefore, the target was only to decrease the exposure to indoor radon. This target was successfully achieved, the efficiency in radon reduction being between 61% and 95%. The average indoor radon, however, was 158 Bqm^{-3}, higher than the national level (Cucoş (Dinu et al., 2017). By the time the batch B was considered for mitigation, Romania had adopted the European recommendations of implementing measures to decrease indoor radon levels exceeding 300 Bqm^{-3} (HG nr526, 2018). Therefore, in case of batch B, the average indoor radon exposure was reduced to concentrations ranging from 23 Bqm^{-3} to 294 Bqm^{-3}.

Although the national criteria were met in all but one house, according to cost-effectiveness studies (Haucke, 2010; Gaskin et al., 2019), these mitigation systems should be tuned in such a way that the radon concentrations decrease to levels below 100 Bqm^{-3}, or according to the ALARA principle (as low as reasonably achievable). It must be emphasized that the only threshold taken into consideration for experimental radon mitigations in Romania was the national recommendation of 300 Bqm^{-3}. On the other hand, the ICA systems linked to the ventilator provides the possibility to adjust the exhaust airflow, thus creating the prospect of decreasing the indoor levels in accordance with the ALARA principle. Long-term monitoring of these houses will be able to show if these mitigation systems alone will suffice in reducing indoor radon below100 Bqm^{-3}. The distribution of individual annual indoor radon concentration pre/post mitigation obtained based on passive monitoring has been represented in Fig. 5.

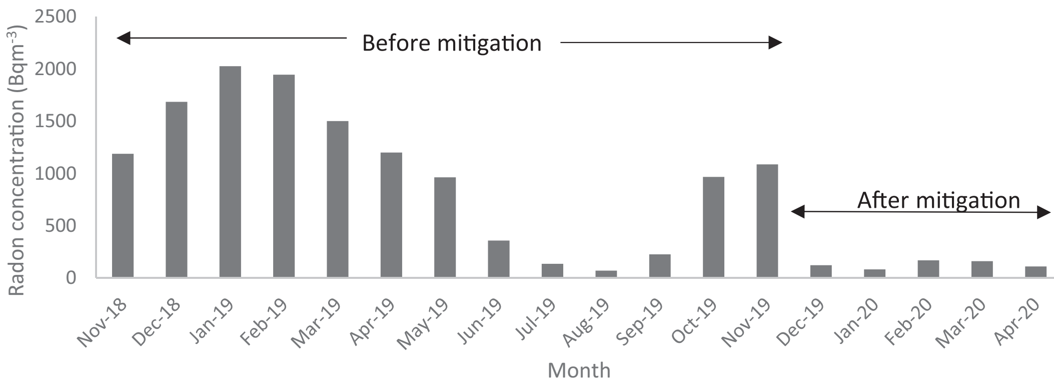

Fig. 3. Monthly distribution of indoor radon concentration (B10).

Additional active monitoring has been used post-mitigation to map the indoor radon levels in each house. Figs. 1 and 6 presents one example of indoor radon distribution before and after the installation of sub-slab depressurization. It can be observed that the radon levels dropped below 100 Bqm^{-3} throughout the house even if the mitigations system serves physically only 3 of the investigated rooms, as it can be seen in Fig. 2.

4. Limitations

Even though the intervention is considered acceptable (WHO, 2016), the mitigation system used has reduced the radon levels as low as possible (ICRP, 2007), it should be stressed that in no time one can be 100% risk free since the goal of complete elimination on indoor radon would be futile (Khan et al., 2019). Although numerous countries have implemented various mitigation measures, systematic follow-up measurements are scarce, creating an unclear perspective of long-term adequate protection. One additional inconvenience could be represented by the increased noise level due to the installation of ventilation (i.e. decentralized ventilation units) in living and sleeping spaces. Although the SSD proved to be the most effective radon mitigation technique, implementing these systems in inhabited houses can represent a serious inconvenience, both in term of costs and disruption of household daily activities. Proper maintenance and the installation of alarms that would be tripped by motor failures or electrical outages are therefore imperative to ensuring long-term low radon levels.

5. Conclusions

Experimental mitigation on 30 existing buildings allowed long-term indoor air quality assessment before and after intervention. This aspect permitted absolute determination of the mitigation efficiency for each house, throughout each house and among the properties studied. Overall, mitigation achieved its objectives, with all properties yielding radon concentrations well below its initial levels. With one exception, a house located in a radon priority area, the indoor radon exposure was decreased to annual concentrations below the recommended level of 300 Bqm^{-3}. Although the radon reduction was between 25% to 95%, the radon concentrations were decreased according to targeted levels. However, one critical conclusion is that the mitigation threshold should never be the nationally or internationally recommended level, but lowest achievable level. The originality of the study lies in the fact that the solutions proposed and implemented represent a step forward towards integrating the common mitigation methods, often reported in the literature, with modern technologies for monitoring and controlling indoor air quality. The novel mitigation approach allows us to provide a more realistic follow-up strategy and long-term cost-benefit analysis. At the time of writing these results, these were the only radon mitigated houses in Romania. Thus, our experimental research has a role of good practices and contributes to the elaboration of specifications for optimal performance of radon and general indoor air quality mitigation systems for dwellings with similar characteristics.

The indoor radon survey carried out by the Babeş-Bolyai Radon Group in Romania, between 2005 and 2020, covers roughly half of the country's territory and yielded a national indoor radon level above the European average, with significant investigated grid cells having annual indoor radon concentrations exceeding the threshold of 300 Bqm^{-3}. Therefore, sustainable education of building engineers, increased public awareness, installation of public grants for radon mitigation and prevention, registration of radon-priority areas in the land utilization maps, and inclusion of regulations and recommendations into building codes are highly required. Redirection of limited health care resources

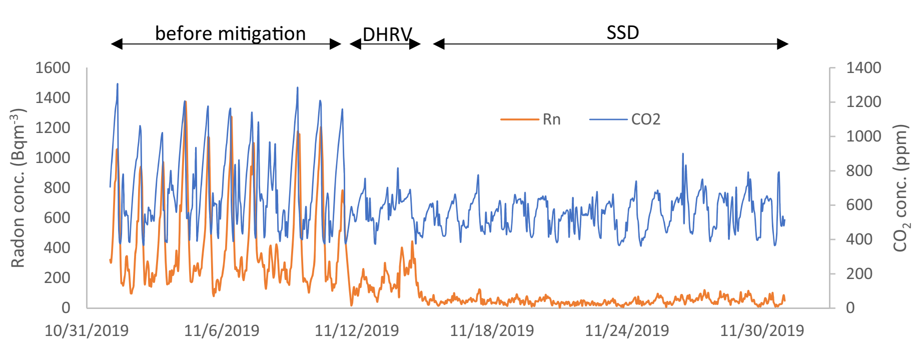

Fig. 4. Impact of different mitigation measures on indoor air quality in house B7.

Table 2
The impact of various mitigation systems on indoor air quality parameters.

House code	Mitigation	Annual radon (Bqm^{-3})/house		Effectiveness (%)	Winter CO_2 (ppm)/house	
		Before	After	Rn reduction	Before	After
B1	- 1 DHRV unit (1 room)	392	294	25	3042	2645
B2	- 2 CHRV units (10 rooms)	426	141	67	1524	584
B3	- 2 DHRV units (2 rooms).	394	141	64	880	677
B4	- 1 CHRV unit (4 rooms)	535	194	64	956	518
B5	- 1 DHRV unit (1 room).	326	239	27	1351	944
B6	- 2 DHRV units (1 room).	385	176	54	1239	700
B7	- 1 SSD (1 room); - 1 DHRV unit (1 room).	423	35	92	785	609
B8	- 1 SSD + Rn barrier (1 room).	377	23	94	673	483
B9	- 1 SSD (3 rooms) + Rn barrier (1 room);	806	138	83	603	489
B10	- 1 SSD + Rn barrier (1 room); - 1 DHRV unit (1 room).	1221	73	94	1700	1243

into preventive radon reduction interventions would reduce lung cancer treatment costs in the future.

The Romanian experience in radon research and implementation of standard measures against elevated radon exposure of the population shows that in less than 10 years reasonable and sustainable solution of radon mitigations have been developed and successfully implemented. This milestone was achieved through permanent communication between scientists, professionals, public and stakeholders and has shown that multidisciplinary research is required on physics, radiation protection, geology, construction engineering and material research.

Radon interventions on residential and public buildings, whether they are preventive or post-construction, should be continuously implemented in Romania to reduce exposures to this very modifiable cause of lung cancer and help reduce the increasing lung cancer burden in an ageing Romanian population.

CRediT authorship contribution statement

B.D. Burghele: Conceptualization, Validation, Writing - original draft, Investigation, Formal analysis. **M. Botoş:** Software, Validation. **S. Beldean-Galea:** Investigation. **A. Cucoş:** Writing - review & editing, Resources, Supervision, Project administration. **T. Catalina:** Methodology. **T. Dicu:** Writing - review & editing, Formal analysis, Project administration. **G. Dobrei:** Investigation. **Ş. Florică:** Investigation. **A. Istrate:** Investigation. **A. Lupulescu:** Investigation, Data curation. **M. Moldovan:** Investigation. **D. Niţă:** Investigation. **B. Papp:** Investigation, Data curation, Validation, Writing - original draft. **I. Pap:** Investigation. **K. Szacsvai:** Investigation. **C. Sainz:** Methodology, Project administration. **A. Tunyagi:** Methodology, Software, Validation. **A. Ţenter:** Conceptualization, Investigation.

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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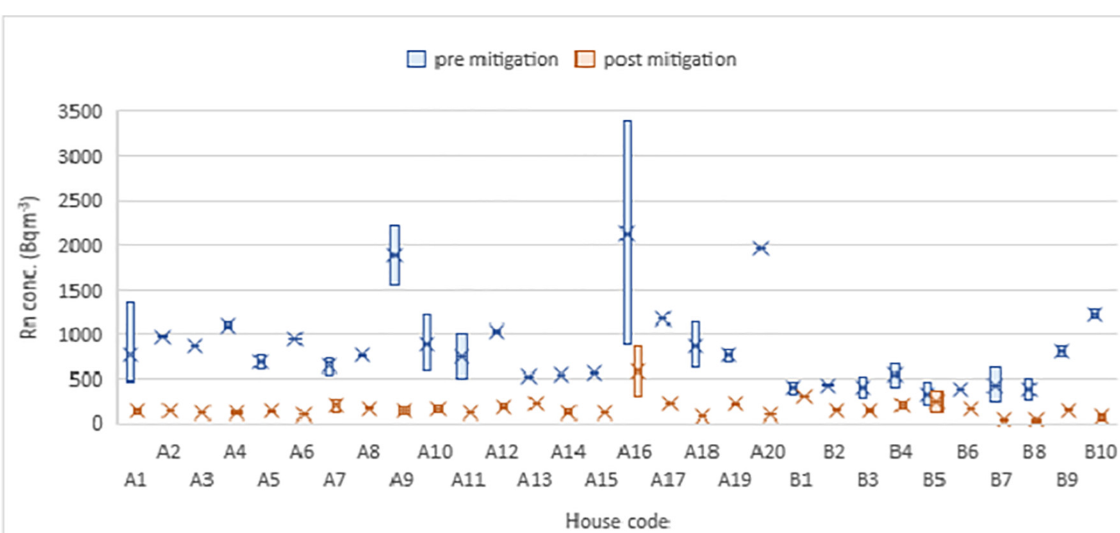

Fig. 5. Distribution of annual indoor radon concentration based on passive monitoring.

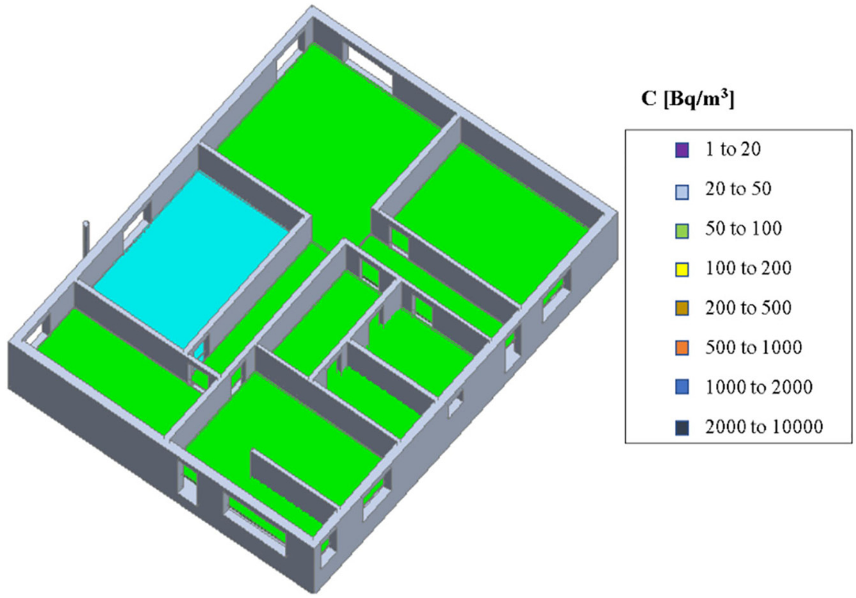

Fig. 6. Indoor radon mapping post mitigation (B9).

Radon linked with Energy Efficiency Optimization of Buildings in Romanian Major Urban Agglomerations SMART-RAD-EN" of the POC Programme (http://www.smartradon.ro/).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.141858.

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