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Review

Mechanisms of Diffusion of Radon in Buildings and Mitigation Techniques

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Abstract: Radon is a naturally occurring radioactive gas found in rocks, soil, and building materials. Precisely because of its gaseous nature, it tends to concentrate in indoor environments, resulting in a danger to human health. The effects of radon have been described, documented, and attested by the international scientific community and recognized as the second cause of lung cancer after cigarette smoking and in synergy with it. In December 2013, the Council of the European Union issued Council Directive 2013/59/Euratom, which establishes basic safety standards relating to protection against the dangers deriving from exposure to ionized radiation and managing the health risks associated with radon. In addition, designing buildings against radon risk in synergy with the use of low environmental impact materials is one of the objectives of building sustainability certifications. This work presents how radon creeps into buildings and reports several technologies that are needed to remove and mitigate the risk associated with indoor radon in existing and new buildings.

Keywords: indoor radon; radon exposure; mitigation techniques; buildings; environmental protection

Citation: Baltrocchi, A.P.D.; Maggi, L.; Dal Lago, B.; Torretta, V.; Szabó, M.; Nasirov, M.; Kabilov, E.; Rada, E.C. Mechanisms of Diffusion of Radon in Buildings and Mitigation Techniques. *Sustainability* **2024**, *16*, 324. https://doi.org/10.3390/su16010324

Academic Editor: Antonio Caggiano

Received: 3 November 2023
Revised: 7 December 2023
Accepted: 25 December 2023
Published: 29 December 2023

1. Introduction

Radon is a radioactive gas found under particular circumstances in rocks, soil, and building materials. Through exhalation, it tends to accumulate in indoor environments, where it can reach concentrations representing a significant risk to the health of the exposed population [1–5]. Radon is an inert gas, colorless, odorless, soluble in water, and denser than air. It is a noble gas. The two main isotopes are Rn-222, which belongs to the U-238 decay chain, and Rn-220, which forms in the Th-232 decay chain [1]. When inhaled, the most significant health hazard from radon exposure is due to its decay products [6]. The decay products of radon lead to the formation of solid chemical elements, which, in the form of aerosols, adhere to the lung tissue after inhalation. Alpha and beta radiation emitted by these radon decay products have a more significant ionization potential than gamma radiation, directly impacting tissues. This interaction has significant implications for human health, as it can stimulate the generation of free radicals and induce direct DNA damage in cells [1–6]. The danger of radon exposure lies in its ability to pose a substantial risk to human health through these complex mechanisms, underscoring the urgent need for awareness and preventative measures.

Radon migration and diffusion in micro and mesoscale pores and cracks involve the gas moving through soil and rock along concentration gradients, driven by advective forces like pressure and temperature variations [1]. Diffusion occurs through pore spaces and cracks, with factors such as soil permeability, porosity, and environmental conditions influencing the ease of radon transport. Microscale pores and mesoscale cracks provide pathways for diffusion, and soil properties, including moisture content and temperature, play crucial roles in these processes [6]. Understanding these mechanisms is vital for assessing radon exposure risks and implementing effective mitigation strategies in diverse geological and environmental contexts.

The effects of radon have been described, documented, and attested by the international scientific community and recognized as the second cause of lung cancer in many countries after cigarette smoking and in synergy with it [7–9]. Despite this, the perception and awareness of the risk of people living in areas prone to exposure to radon seems disproportionately low [9,10], similar to the existing policies and fighting measures [11].

In the European legal framework, the Council of the European Union has issued Directive 2013/59/Euratom, which establishes basic safety standards for protection against the dangers of exposure to ionizing radiation [2,12]. The radon hazard is classified as external (gamma) and internal (alpha) indexes. Whilst the former can express the natural hazard coming from the geological structure, the latter expresses the indoor hazard as a function of multiple additional parameters concerning the dwellings and their inhabitants. Regarding radon in buildings, the recommendation has suggested an average concentration of 300 Bq m^{-3} in existing dwellings and 200 Bq m^{-3} in those built from January 2025. In addition, member states must update the National Radon Action Plan (NRAP); in Italy, the current NRAP was published in 2002 [13] and currently needs updating [14].

Furthermore, to achieve the goal of CO_2 neutrality as indicated in the new European Green Deal, the environmental certifications to guarantee sustainable construction are increasingly important together with the whole waste management, including construction and demolition ones, in accordance with circular economy concepts [15–18]. Among the most widespread certifications in the world is the Leadership in Energy and Environment Design (LEED), a voluntary certification created in 1988 by the US Green Building Council (USGBC). In addition to energy performance standards, this certification provides for the achievement of living comfort levels: for example, the use of measures to improve the air quality of indoor environments and systems to reduce exposure to toxic agents [19,20]. In detail, the LEED certification evaluates six macro-sections: sustainability of the construction site, efficient water management, energy and the environment, materials and resources, location and transport, and finally, the quality of the air in indoor environments [21]. The mandatory prerequisite of the latter is the presence of systems for controlling contamination generated by human activities and for protection against radon. From this, it emerges that considering the risk associated with radon exposure is a fundamental part of designing and building sustainably.

Knowledge of indoor radon sources is essential for adopting precautions for new buildings and being able to undertake remedial actions in existing buildings. This work reports how radon risk is identified, how it creeps into buildings, and what technologies are used to decrease indoor concentration in existing and new buildings.

2. Mapping

In recent years, several studies have been performed throughout the world to identify the areas most exposed to radon hazard in terms of geogenic potential, according to different techniques and methodologies, which may be subdivided into geostatistical [22–28], based on geochemical/geological models of the territory, eventually combined with Geographical Information Systems (GIS) [25,29], and non-geologically based techniques based on statistics [30] typically empirically based on the survey of emissions. Such survey activities have been conducted and disseminated in several countries, including Austria [26,31], Belgium [25,32,33], Bulgaria [34], Canada [35], China [36–38], Egypt [39], Finland [40], France [29], Germany [41], Greenland [42], Iran [43], Ireland [11], Mexico [44], Norway [45], Poland [46,47], Romania [48], Russia [49], Spain [50–52], Sweden [53,54], Switzerland [55], the UK [56–58], the USA [59–64], Uzbekistan [65], and Italy [27,28,66–71]. It is noted that a priori identification of rock types likely to be implicated in radon hazard is difficult and likely to be successful in only a few cases [72], and measurements of radon concentrations in soil give only limited information about the radon concentrations to be expected in new buildings [73]. Thus, techniques combining geological models and field surveys are deemed the most reliable. Very recently, novel techniques have been proposed based on fuzzy logic [74] or Artificial Intelligence (AI) and Machine Learning (ML) based on extreme gradient boosting (XGBoost) models and deep neural networks (DNNs) combining indoor radon measurement records, property registers, and geogenic information [54]. Analyzing the single case of Italy for the sake of conciseness, the national weighted average for the population was 70 Bq m^{-3}. As shown in Figure 1, the situation is, however, very diversified in the Italian regions: the average concentration of radon is from 20 to 40 Bq m^{-3} in the Liguria, Marche, and Basilicata regions to around 80–120 Bq m^{-3} in Campania, Lazio, Lombardy, and Friuli-Venezia Giulia [71,75].

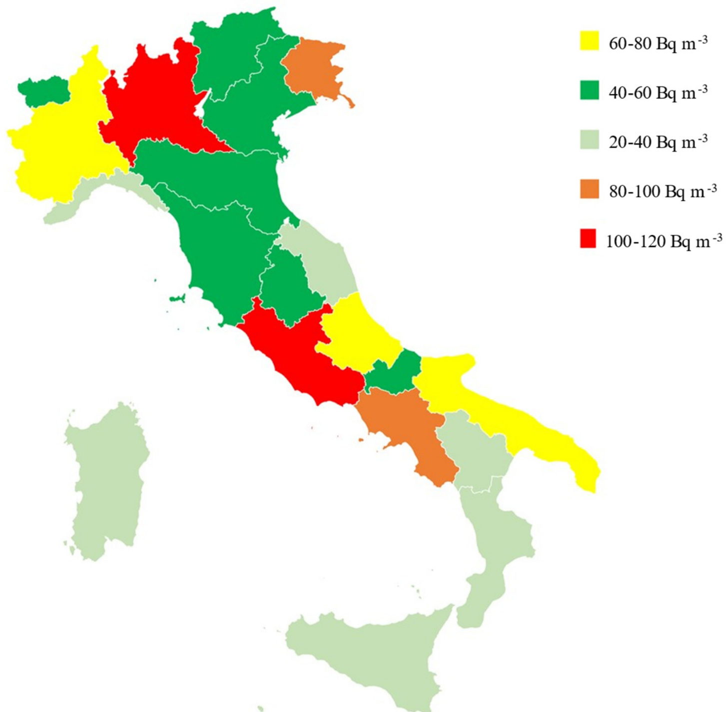


Figure 1. Average radon concentration in Italian regions (adapted from [71]).

3. Radon in Buildings

The role of building materials as a source of indoor radon, typically concrete components [76–80] such as specific supplementary cementitious materials or aggregates, specific ceramic or rock tiles [81], specific masonry blocks [76–78], and fillers for historical vaults, thick bearing walls and floors [82], is generally minor compared to the soil. The contribution of building materials to the world's average radon concentration in dwellings is estimated at around 15–20%, corresponding to a radon concentration of around 10–15 Bq m^{-3} [83]. However, some situations differ significantly from these values; building materials of natural origin obtained from soils particularly rich in U-238 and Th-232 could have concentrations of activity even 10–20 times higher than the estimated average. In Sweden, for example, since the 1950s, it was found that concrete employing aggregates with a high percentage of alum shale had a high concentration of Ra-226, producing a significant concentration contribution of Rn-222, up to about 400 Bq m^{-3} [76]. Subsequently, materials of natural origin with a high radioactivity content were also identified in other countries, such as certain granites, particularly in central-southern Italy [84], where natural pozzolanic binders were found to have similar properties. Among the materials with a high concentration of activity, in addition to those of natural origin, there are also materials composed of products resulting from industrial processes such as gypsum, a by-product of the phosphate industry, and coal ash, a by-product of fuel-fired power plant solids. These materials can have very high Ra-226 concentrations and make the building material an essential source of radon [85]. Similar considerations apply to concrete or ceramic binders coming from blast furnace slag or to masonry blocks containing red mud from the aluminum production chain. Whether the building material has its own radon content or whether it became exposed to radon gas and/or contaminated water coming from the contact ground, the exhalation into the built environments occurs through the materials. Therefore, the characterization of the exhalation rate of materials is of crucial importance to determine the potential radon risk. The radon hazard from building materials is typically characterized by laboratory testing on samples, for example, with spectroscopic methods [79,80,86–88] or employing in the laboratory similar devices and techniques used for the indoor survey [89–91], and numerical models have been proposed and fine-tuned to predict radon flux, exhalation rate, and emanation fraction from different materials [92–95]. Critical Wall Radon Exhalation Flux (WRF), above which the radon risk may be relevant and worth survey and investigation, is set by some authors at 10×10^{-3} Bq·m^{-2}·s^{-1} [94]. It is noted that a high increase in the exhalation rate depends upon humidity conditions since it is experimentally assessed that the exhalation rate can exponentially increase with absolute humidity [96,97].

As previously mentioned, usually, the primary source of indoor radon is soil, depending on the geological sub-structure of the site [98] or on the presence of nuclear waste in the area [48]. Depending on the mechanisms of radon diffusion from the ground, the premises of buildings located in the basement or on the ground floor are generally those particularly affected by the phenomenon [99]. Indeed, the main factors determining the risk of exposure to radon are geological (subsoil structure composition); technological, referring to the building (cellar floor permeability, cellar aeration, air-tightness of the homes); and behavioral, referring to the inhabitants (aeration habits of the occupants, tendency to spend time in environments in contact with the ground) [100–103]. In addition to the ground, radon could be present in domestic water [104] and thus enter into apartments on higher floors [105]. Radon in water can contribute up to 15% of the total exposure [106,107]. Aeration, depending on cellar passive aeration, airtightness of the building surfaces, and the tendency of the inhabitants to leave windows open, plays a crucial role in determining the indoor radon concentration, which increases when ventilation is low and there is little air exchange rate [91,108]. The concentration of radon can undergo significant daily and seasonal variations [36,46,75,109,110]. Typically, the highest values are observed in the early morning hours, when the temperature difference between the inside and the outside is more significant [111] although, rather than temperature, the driving phenomenon is the pressure gradient, which may also depend upon atmospheric fluctuations and wind conditions [112–116].

For the same reason, in winter, the concentrations are, on average, higher than in summer, but the variability is very high [117]. For example, in South Tyrol, the radon concentration in houses increases when the ground freezes. Frost probably hinders radon's escape from the ground, favoring its escape where the ground is not frozen. For the above reasons, typical detection measurements are carried out with passive dosimeters alternatively based on solid-state nuclear track [118], active carbons, or electrets, which are installed in the environment and are recommended to be monitored for a full year continuously. Using passive dosimeters allows individuation of the mean annual radon exposure. Active instruments such as spark or ionization chambers are employed when the daily variation is interesting.

The type of building and quality have a fundamental role in the entry of radon, favored by cracks in the floors and the lack of sealing; for example, the points where the service pipes enter the building [112]. It should be emphasized that prefabricated construction techniques (e.g., precast concrete large panel structures) are critical at this level due to many structural and non-structural joints, constituting possible preferential gas entryways [13].

The pressure difference between the inside and outside of buildings is the primary mechanism that transports radon from the ground in indoor environments. Generally, the interior of a building is depressed compared to the outside, so there is a suction of air from the ground through the cracks and openings present in the structure of the building [113,114]. It is noted that, following the growing global interest toward reduction of the anthropic environmental impact, many energy-inefficient buildings and dwellings have recently or are currently being subjected to energy retrofitting, with interventions which, in the case of the European Union, are apparently going to be mandatory based on specific directives. Such interventions are typically carried out by adding internal or external thermal insulation layers and replacing window frames with more thermally efficient ones. Whether such interventions are implemented together with a proper mechanical ventilation system or not, they strongly reduce the permeability of the building envelope, with possible repercussions on indoor air quality and a potential increase in exposure to radon [108,119–126].

Whatever the source of indoor radon (soil, building materials, or water), the concentration in buildings varies from 10 to 70,000 Bq m^{-3} [127]. The world average value is around 40 Bq m^{-3} [83]. Figure 2 shows the entry routes of radon into a building.

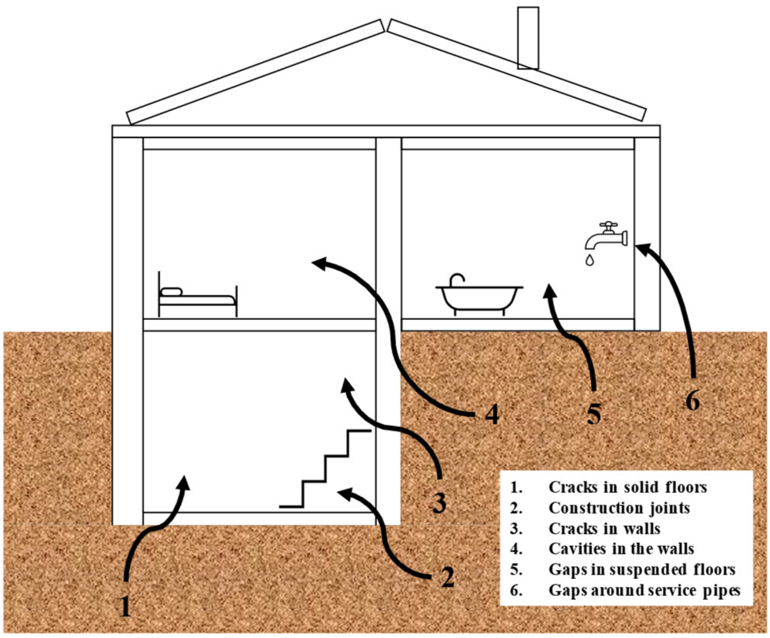


Figure 2. Radon entry routes into a building (adapted from [6]).

Another isotope of radon that could be found in significant amounts indoors is Rn-220, the radioactive decay product of Th-232 and, therefore, known as thoron. It is characterized by a short half-life of 55.6 s, which strongly limits its diffusion in the environment. There is considerable variability in concentration from one place to another, but concentration levels are generally within the range of 0.2–12 Bq m^{-3} [128]. In recent years, interest in thoron has grown considerably; due to its short half-life, the concentration in dwellings comes more from building materials than the soil. An example is given by the tuff of central-southern Italy, which is particularly rich in this isotope [113]. Some studies have also shown that in some exceptional cases, as in the case of dwellings built in natural cavities in the Chinese provinces of Shanxi and Shaanxi, the concentration of thoron decay products may be higher than those of radon offspring [129,130].

4. Mitigation Systems

Knowledge of indoor radon sources is essential to making proper, cost-effective design decisions for new buildings and to tackle remedial actions in existing buildings [131–133]. As seen above, soil, building materials, and contaminated aquifers contribute in different proportions to the concentration found in indoor environments. Below are some mitigation systems, divided into direct and indirect, and precautions for new buildings.

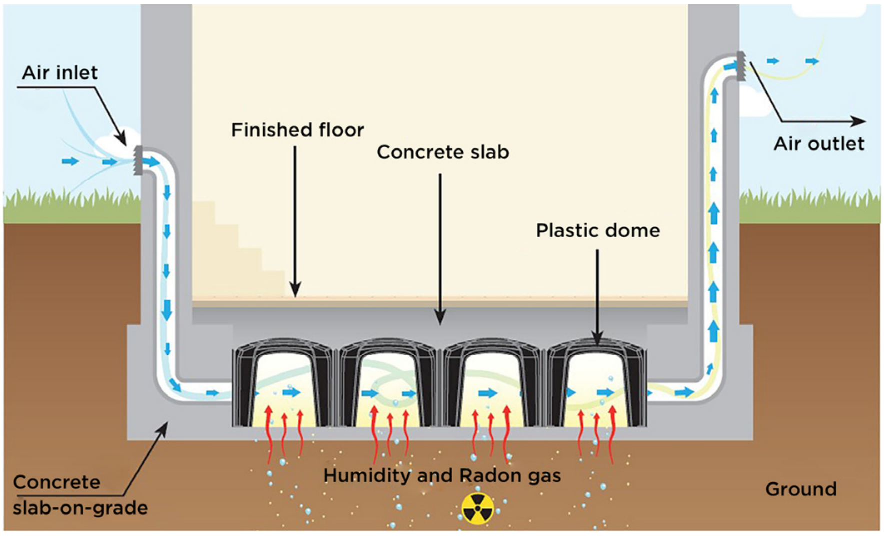
Direct systems act directly on the indoor air through special equipment that can reduce the radon concentration and its decay products. They alter the composition of the air and, consequently, the expected behavior of radon and its decay products. From the literature analysis, it clearly emerges that the most recommended technique is soil depressurization by acting with radon pipes below the slab-on-grade or with radon wells right outside the building plan [134–146]. Pressurization of the building is an arguable technique since it is effective in some situations [140] but ineffective in other ones [112]. Mechanical ventilation was proved to be efficient in many situations [40,141,147], although the efficiency of the mechanism of radon dilution and transport outdoors did not increase much with respect to the correct activation of passive natural ventilation [112]. Moreover, the installation of HEPA and carbon-active filters had a controversial effect [148,149]. The use of electrostatic precipitators yielded promising outcomes [150].

A specific reduction in the concentration of radon with these techniques is not necessarily correlated to a reduction in risk, especially if they are not supplied continuously and properly maintained; i.e., the radon concentration can be mitigated during the treatment, but after some time after the treatment is supplied, the concentration may come back to the original level [151] if additional passive measures are not provided as well. For these reasons, it is insufficient to apply such systems alone in buildings with high gas concentrations [149]. Single applications are recommended in those buildings where the concentrations slightly exceed the risk levels or in environments where an existing ventilation system can be easily and economically adapted to the purpose, and eventually repeated periodically. As stated in [152], parameters such as the configuration of the house, the age of the house, and whether the measures are installed by a major contractor, a local builder, or the householder can affect the effectiveness of the selected solution or combination of solutions. The most common techniques and devices are summarized in Table 1.

Indirect systems are another intervention that reduces radon entry from the ground into the building. These techniques apply to buildings, both under construction and existing, on the ground or underground floor or with rooms in direct contact with the soil through slabs or walls on grade. The most typical intervention, as shown in Figure 3, consists of aerating the cellar with a system of low-cost small domes of different depths, which are placed over the concrete slab-on-grade. After they are inter-connected among different fields and with vertical inlets/outlets, the reinforced concrete pavement is cast above them. It is to be noted that the dome elements cannot be placed in correspondence with the structural foundation elements, either if they are punctual (isolated foundations) or a grid of beams (continuous inverted beams). This system is not compatible with plate foundations. It is noted that this system may allow a great reduction in the radon diffusion within the environment [112,137] by natural dilution and dispersion of the gas, although it does not represent alone a perfect barrier due to the unavoidable presence of non-ventilated areas where the structural foundation elements are present (e.g., the foundation beam grid to be cast in Figure 3), and to the possible presence of cracks in the concrete slab. Its effectiveness is typically increased with the combination of a waterproofing layer positioned either below or above the concrete slab [153]. The efficiency of typical membranes used as waterproofing horizontal layers or vertical vapor-proof layers is analyzed experimentally in [76,154–156], despite experimental evidence suggesting that membranes alone, i.e., without ventilation of the cellar, may fail in limiting the radon exhalation [135,141]. Nevertheless, positive experiences were reported in [157]. Polymer-based cement plasters were assessed as an alternative to traditional bitumen and polymeric products [158]. The indirect systems with their description are shown in Table 2.

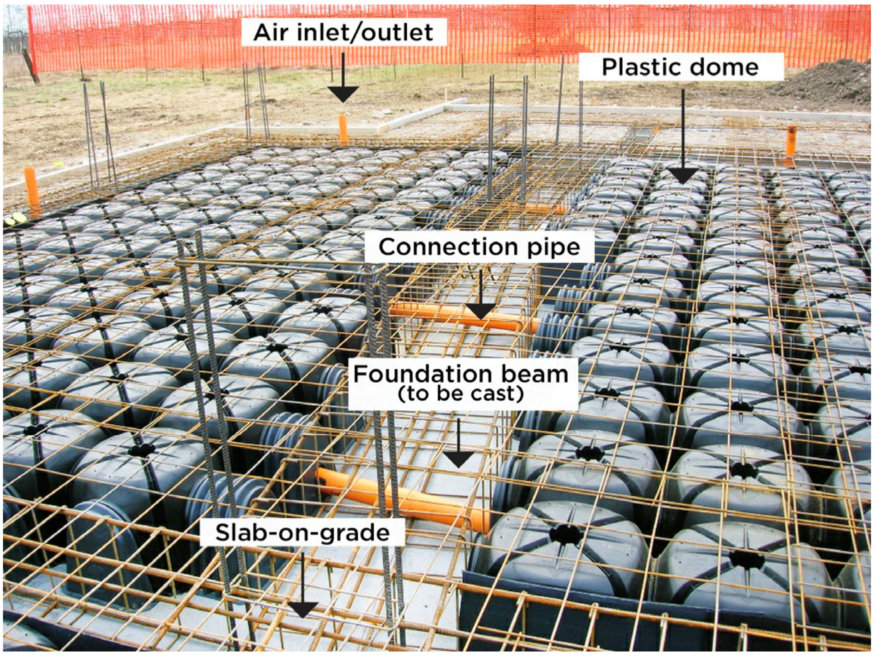
Table 1. Direct systems and their description.

System	Description	References
Electrostatic precipitators/Ion generators	Electrostatic precipitators use an electric field to attract and collect charged radon particles, preventing their release into the air. On the other hand, ion generators produce ions that attach to radon particles, making them heavier and more likely to settle, reducing their presence in the air. Both technologies aim to minimize radon concentrations by collecting or altering radon particles' behavior.	[150]
Mechanical ventilation	Fans are used to increase mechanical ventilation to cause air movement; consequently, they favor the deposition of radon decay products on surfaces and reduce their concentration in the air. Fans can usually be combined with heat exchangers, which allows for limiting heat dispersion during ventilation operations. They can also be combined with filters, some specific for radon mitigation based on activated carbon-type materials that can retain the atmospheric detail on which a fraction of the radon decay products is attached.	[40,141,147]
Pressurization of the building	This technique involves reducing, and possibly reversing, the pressure difference between the inside and outside of the building through the forced introduction of air that puts pressure on the building itself, reducing the cause that generates the entry of radon. It should be noted that the overpressure of buildings has some possible drawbacks: in addition to the difficulty of achieving positive pressure due to the poor tightness of the buildings as a whole and the cost of a ventilation system, pressurizing the building commits the occupants to observe a specific behavior, such as the habit of opening windows, and can decrease, again due to the greater exchange of air, the preservation of heat, with consequent increases in energy consumption and cost.	[112,140]
Soil depressurization	The technique consists of constructing a well of about 0.2–0.5 m^3 below (sub-slab) or near the building (well) where the remedial action must be operated. In the well, a depression is produced through fans, and consequently, the radon present in the surrounding soil is sucked outwards and then diverted from its path to the inside of the building. Soil depressurization is suitable for buildings with a high radon concentration and sometimes represents the only effective solution.	[134–146]



(a)

Figure 3. *Cont.*



(**b**)

Figure 3. Typical ventilated cellar: (**a**) mechanism; (**b**) picture.

Table 2. Indirect systems and their description.

System	Description	References
Ventilation of the cellar/crawl space	Increasing the natural ventilation of the crawl space by installing a fan for forced ventilation or opening vents for air passage dilutes the radon concentration. Forced ventilation can be achieved by pushing or sucking air: in the first case, in addition to mixing with air low in radon coming from the outside, it is possible to obtain, through appropriate regulation of the incoming and outgoing flow rates, also an effect of overpressure concerning the ground that counteracts the emission of radon toward the crawl space itself, in analogy to the principles of ionization of the building. In the second case, the air entering the crawl space is taken not from the outside but from inside the building, thus also combining the effect of increasing ventilation of the building itself.	[112,137]
Sealing of the entrance routes from the ground	It may be partial or total; partial sealing is used for the individual visible cracks in the floors, the floor wall joints, and the passages of the services. However, cracks are often not easily identified and sometimes not reachable. The total sealing is borne by the entire surface of the decking and possibly the walls in direct contact with the ground. Some specially tested products have very low or negligible radon permeability, such as polyethene or materials coupled in multiple layers with aluminum or PVC. In some cases, these barriers are rigid and are produced in such a way as to form a gap of a few millimeters between the floor and the covering. In addition, a natural or forced ventilation system can be applied to suck the radon in the cavities. Radon penetration in concrete members on grade can also be mitigated by installing during construction a waterproofing layer laying either below the slab-on-grade in order to mitigate the entrance of the gas through it or, with less efficacy in reducing the possible permeability bridges, above the slab-on-grade.	[143,155]
Sealing of the entrance routes from the walls	In those cases where the emission comes from the walls, either by intrinsic radon concentration or by permeability through them, a reduction in radon concentration can be obtained by applying synthetic coatings. Polyvinyl materials or epoxy resins can reduce the emission by an order of magnitude after a necessary and accurate preparation work of the base.	[143,155]

Finally, the precautions to be followed when constructing new buildings are reported. In fact, during construction, adopting special measures creates conditions to prevent or at least reduce radon entry. The most important factors are shown in Table 3.

Table 3. Precautions for new buildings.

System	Description	References
Choice of building materials	Generally, for the construction of foundations and walls in the underground parts, concrete gives the most significant guarantees of radon insulation and is preferred to perforated bricks. Regarding the upper part of the house, from this point of view, the choice of materials is less critical.	[86,87,89]
Design and use of premises	As a rule, the radon problem mainly concerns environments in direct contact with the ground. However, houses on the ground floor above cellars or empty rooms are also affected. Therefore, it would be appropriate to discourage using basements for residential purposes. Garages or storage always open on the ground floor or basement can protect the upper rooms from radon, particularly in crawl spaces. All strategies separating the premises from the ground help prevent radon ingress.	[112,137]
Stairs, elevator shafts, vertical ducts, chimneys	During the design phase, communication channels between inhabited areas and areas in contact with the ground must be avoided or treated since they can facilitate radon transport in the inhabited part of the house. Stairs leading to cellars should be able to be closed at least in one place with a well-sealed door.	[143]
Passages of pipelines from the ground	Any plant part of the building that penetrates the ground constitutes a potential radon infiltration point. Water and gas pipes should be introduced from the side walls, not the floor, ensuring good pipe ventilation near the building. The same applies to small-diameter pipes, such as electrical and antenna cables, which must be sealed with elastic materials. The sewage system should cross the cellar floor in as few places as possible.	[143]
Thermal insulation	A state-of-the-art building should have a thermal insulation layer and an appropriate waterproofing sheath between heated and unheated rooms. Even in the case of external insulation of the walls of a building, where vapor condensation is harder to occur, care must be taken. Radon can spread to the upper floors through the gaps in the insulating layer if the insulating coating penetrates the ground. It is essential to completely seal the insulating layer or to install short stoppers to avoid radon penetrating indoors.	[143,153]

According to a survey conducted in Switzerland, only 46% of the buildings where a radon concentration of 1000 Bq m^{-3} was exceeded underwent remediation actions, the main cause being the high costs of the intervention work [159]. It is, however, promising that further surveying conducted in the UK proved that after proper regulations aimed at fighting the exposure to radon were put in place by the government, the concentration dropped significantly [57,133], indicating that imposing passive means of protection is effective. Moreover, in combination with the passive means of protection, the new constructions or the existing ones undergoing extensive retrofitting should be provided with the predisposition to apply an active measure to smartly and rapidly solve those cases where passive measures may not be enough to mitigate the phenomenon and bring the radon concentration below the target one.

5. Discussion

The health risk linked to the presence of radon is more severe than previously thought, and in the light of currently available knowledge, radon has become a health problem of utmost importance. In 2013, the European Council issued the Council Directive 2013/59/Euratom, which establishes basic safety standards relating to protection against the dangers deriving from exposure to radiation, and it recommends lower indoor radon concentration values in existing and new buildings. Moreover, some voluntary building certifications such as LEED include systems for improving the comfort of closed environments in the requirements, including mitigating the radon risk.

Considering the persistently low levels of risk perception within the population, it becomes imperative to implement interventions that elucidate and disseminate a clear and comprehensive understanding of associated risks. Elevating public awareness is paramount, as heightened consciousness would likely prompt a more concerted emphasis on developing and implementing mitigation systems. These systems play a crucial role in minimizing exposure to radon gas. This study aims to foster awareness of the issue and propose practical solutions to reduce the inherent risks.

6. Conclusions

This work presents how radon risk is mapped, how it creeps into buildings, and what technologies are used to decrease indoor concentration. In total, four direct systems that allow the removal of indoor radon, three indirect systems that limit the percolation of gas and contaminated water, and five precautions for buildings under construction are described. Improving the safety of new buildings and adapting existing ones through the techniques described are essential to ensure health protection for the population. The sustainable design of new buildings or retrofitting of existing ones must be carried out in synergy with the mitigation systems of pollutants such as radon.

In summary, this review could be interesting for the following several reasons:

1. Public health: radon is a natural radioactive gas that can infiltrate buildings, increasing the risk of lung cancer in case of exposure to high levels over time. Radon pollution is indiscriminate in its impact, affecting individuals across various demographics. The heightened prevalence of severe conditions, notably lung cancer, underscores the urgency of addressing this public health concern. Despite the significant health implications, a notable lack of awareness exists regarding the potential dangers of radon contamination. Increased public awareness and the implementation of targeted preventive measures shown in this study are imperative to mitigate the widespread health risks associated with radon exposure.
2. Regulations and laws: many countries have regulations requiring radon mitigation. A review of radon mitigation systems can be helpful for anyone involved in building design, construction, or renovation.
3. Sustainability: radon mitigation can be integrated into sustainable construction projects, improving indoor air quality and avoiding unnecessary energy losses. This aspect is becoming increasingly relevant in the context of sustainable building.
4. Technological innovation: research and development of new technologies for radon mitigation are ongoing. This review could highlight the latest discoveries and innovative solutions in the field.
5. Awareness: educating the public and professionals on the issues is essential to raising awareness about radon and mitigation systems. This review can contribute to this awareness effort.

Generally, this review can interest anyone involved in construction, public health, and scientific research.

Author Contributions: Conceptualization: A.P.D.B., L.M., V.T. and B.D.L.; methodology: A.P.D.B. and L.M.; validation: V.T., B.D.L., M.S., M.N., E.K. and E.C.R.; investigation: A.P.D.B., L.M. and B.D.L.; data curation, A.P.D.B. and L.M.; writing—original draft preparation, A.P.D.B., L.M., V.T. and B.D.L.; writing—review and editing, V.T., M.S., M.N., E.K. and E.C.R.; visualization: V.T., B.D.L. and E.C.R.; supervision: V.T., M.S., M.N., E.K., and E.C.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

References

1. International Agency for Research on Cancer. *Man-Made Mineral Fibres and Radon*; World Health Organization: Geneva, Switzerland, 1988; Available online: https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Man-Made-Mineral-Fibres-And-Radon-1988 (accessed on 29 October 2023).
2. Nunes, L.J.R.; Curado, A.; da Graça, L.C.C.; Soares, S.; Lopes, S.I. Impacts of Indoor Radon on Health: A Comprehensive Review on Causes, Assessment and Remediation Strategies. *Int. J. Environ. Res. Public Health* **2022**, *19*, 3929. [CrossRef] [PubMed]
3. Dimitroulopoulou, S.; Dudzińska, M.R.; Gunnarsen, L.; Hägerhed, L.; Maula, H.; Singh, R.; Toyinbo, O.; Haverinen-Shaughnessy, U. Indoor air quality guidelines from across the world: An appraisal considering energy saving, health, productivity, and comfort. *Environ. Int.* **2023**, *178*, 108127. [CrossRef] [PubMed]
4. Wei, G.; Yu, X.; Fang, L.; Wang, Q.; Tanaka, T.; Amano, K.; Yang, X. A review and comparison of the indoor air quality requirements in selected building standards and certifications. *Build. Environ.* **2022**, *226*, 109709. [CrossRef]
5. Jones, A.P. Indoor air quality and health. *Atmosph. Environ.* **1999**, *33*, 4535–4564. [CrossRef]
6. International Commission on Radiological Protection (ICRP). Radiological Protection against Radon Exposure. 2014. Available online: https://www.icrp.org/publication.asp?id=ICRP%20Publication%20126 (accessed on 29 October 2023).
7. Vogeltanz-Holm, N.; Schwartz, G.G. Radon and lung cancer: What does the public really know? *J. Environ. Radioact.* **2018**, *192*, 26–31. [CrossRef] [PubMed]
8. Darby, S.; Hill, D.; Auvinen, A.; Barros-Dios, J.M.; Baysson, H.; Bochicchio, F.; Deo, H.; Falk, R.; Forastiere, F.; Hakama, M.; et al. Radon in homes and risk of lung cancer: Collaborative analysis of individual data from 13 European case-control studies. *Br. Med. J.* **2005**, *330*, 223–226. [CrossRef]
9. Darby, S.; Hill, D.; Deo, H.; Auvinen, A.; Barros-Dios, J.M.; Baysson, H.; Bochicchio, F.; Falk, R.; Farchi, S.; Figueiras, A.; et al. Residential Radon and lung cancer—Detailed results of a collaborative analysis of individual data on 7148 persons with lung cancer and 14, 208 persons without lung cancer from 13 epidemiologic studies in Europe. *Scand. J. Work Environ. Health* **2006**, *32*, 1–83.
10. Cori, L.; Curzio, O.; Donzelli, G.; Bustaffa, E.; Bianchi, F. A Systematic Review of Radon Risk Perception, Awareness, and Knowledge: Risk Communication Options. *Sustainability* **2022**, *14*, 10505. [CrossRef]
11. Lacchia, A.R.; Schuitema, G.; Banerjee, A. "Following the Science": In Search of Evidence-Based Policy for Indoor Air Pollution from Radon in Ireland. *Sustainability* **2020**, *12*, 9197. [CrossRef]
12. Council of the European Union. Council Directive 2013/59/Euratom of 5 December 2013 Laying down Basic Safety Standards for Protection against the Dangers Arising from Exposure to Ionising Radiation, and Repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom. 2013. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2014:013:0001:0073:EN:PDF (accessed on 29 October 2023).
13. Ministero della Salute. Piano Nazionale Radon. 2002. Available online: https://www.salute.gov.it/portale/documentazione/p6_2_2_1.jsp?lingua=italiano&id=2436 (accessed on 29 October 2023).
14. Bochicchio, F.; Antignani, S.; Carpentieri, C.; Ampollini, M.; Caccia, B.; Pozzi, S.; Venoso, G. The national Radon archive as a useful tool for developing and updating the national Radon action plan. *Radiat. Prot. Dosim.* **2017**, *177*, 99–103. [CrossRef]
15. Perissi, I.; Jones, A. Investigating european union decarbonization strategies: Evaluating the pathway to carbon neutrality by 2050. *Sustainability* **2022**, *14*, 4728. [CrossRef]
16. Ohene, E.; Chan, A.P.C.; Darko, A.; Nani, G. Navigating toward net zero by 2050: Drivers, barriers, and strategies for net zero carbon buildings in an emerging market. *Build. Environ.* **2023**, *242*, 110472. [CrossRef]
17. Ragazzi, M.; Fedrizzi, S.; Rada, E.C.; Ionescu, G.; Ciudin, R.; Cioca, L.I. Experiencing urban mining in an italian municipality towards a circular economy vision. *Energy Procedia* **2017**, *119*, 192–200. [CrossRef]
18. Ossio, F.; Salinas, C.; Hernández, H. Circular economy in the built environment: A systematic literature review and definition of the circular construction concept. *J. Clean. Prod.* **2013**, *414*, 137738. [CrossRef]
19. Awadh, O. Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis. *J. Build. Eng.* **2017**, *11*, 25–29. [CrossRef]
20. Vosoughkhosravi, S.; Dixon-Grasso, L.; Jafari, A. The impact of LEED certification on energy performance and occupant satisfaction: A case study of residential college buildings. *J. Build. Eng.* **2022**, *59*, 105097. [CrossRef]
21. Istil, S.A.; Górecki, J.; Diemer, A. Study on certification criteria of building energy and environmental performance in the context of achieving climate neutrality. *Sustainability* **2023**, *15*, 2770. [CrossRef]
22. Buttafuoco, G.; Tallarico, A.; Falcone, G. Mapping soil gas Radon concentration: A comparative study of geostatistical methods. *Environ. Monit. Assess.* **2007**, *131*, 135–151. [CrossRef]
23. Raspa, G.; Salvi, F.; Torri, G. Probability mapping of indoor Radon-prone areas using disjunctive kriging. *Radiat. Prot. Dosim.* **2010**, *138*, 3–19. [CrossRef]
24. Borgoni, R.; Quatto, P.; Somà, G.; de Bartolo, D. A geostatistical approach to define guidelines for Radon prone area identification. *Stat. Methods Appl.* **2010**, *19*, 255–276. [CrossRef]
25. Zhu, H.C.; Charlet, J.M.; Poffijn, A. Radon risk mapping in southern Belgium: An application of geostatistical and GIS techniques. *Sci. Total Environ.* **2001**, *272*, 203–210. [CrossRef] [PubMed]
26. Dubois, G.; Bossew, P.; Friedmann, H. A geostatistical autopsy of the Austrian indoor Radon survey (1992–2002). *Sci. Total Environ.* **2007**, *377*, 378–395. [CrossRef] [PubMed]

27. Bertolo, A.; Bigliotto, C.; Giovani, C.; Garavaglia, M.; Spinella, M.; Verdi, L.; Pegoretti, S. Spatial distribution of indoor Radon in Triveneto (northern Italy): A geostatistical approach. *Radiat. Prot. Dosim.* **2009**, *137*, 318–323. [CrossRef]
28. Borgoni, R.; Tritto, V.; Bigliotto, C.; de Bartolo, D. A Geostatistical Approach to Assess the Spatial Association between Indoor Radon Concentration, Geological Features and Building Characteristics: The Case of Lombardy, Northern Italy. *Int. J. Environ. Res. Pub. Health* **2011**, *8*, 1420–1440. [CrossRef] [PubMed]
29. Ielsch, G.; Cushing, M.E.; Combes, P.; Cuney, M. Mapping of the geogenic Radon potential in France to improve Radon risk management: Methodology and first application to region Bourgogne. *J. Environ. Radioact.* **2010**, *101*, 813–820. [CrossRef] [PubMed]
30. Murphy, P.; Organo, C. A comparative study of lognormal, gamma and beta modelling in Radon mapping with recommendations regarding bias, sample sizes and the treatment of outliers. *J. Radiol. Prot.* **2008**, *28*, 293–302. [CrossRef] [PubMed]
31. Bossew, P.; Dubois, G.; Tollefsen, T. Investigations on indoor Radon in Austria, part 2: Geological classes as categorical external drift for spatial modelling of the Radon potential. *J. Environ. Radioact.* **2008**, *99*, 81–97. [CrossRef] [PubMed]
32. Cinelli, G.; Tondeur, F.; Dehandschutter, B. Development of an indoor Radon risk map of the Walloon region of Belgium, integrating geological information. *Environ. Earth Sci.* **2011**, *62*, 809–819. [CrossRef]
33. Zhu, H.C.; Charlet, J.M.; Tondeur, F. Geological controls to the indoor Radon distribution in southern Belgium. *Sci. Total Environ.* **1998**, *220*, 195–214. [CrossRef]
34. Ivanova, K.; Stojanovska, Z.; Djunakova, D.; Djounova, J. Analysis of the spatial distribution of the indoor Radon concentration in school's buildings in Plovdiv province, Bulgaria. *Build. Environ.* **2021**, *204*, 108122. [CrossRef]
35. Whyte, J.; Falcomer, R.; Chen, J. A Comparative Study of Radon Levels in Federal Buildings and Residential Homes in Canada. *Health Phys.* **2019**, *117*, 242–247. [CrossRef] [PubMed]
36. Li, X.; Zheng, B.; Wang, Y.; Wang, X. A study of daily and seasonal variations of Radon concentrations in underground buildings. *J. Environ. Radioact.* **2006**, *87*, 101–106. [CrossRef] [PubMed]
37. Li, X.; Zheng, B.; Wang, Y.; Wang, X. A survey of Radon level in underground buildings in China. *Environ. Int.* **2006**, *32*, 600–605. [CrossRef] [PubMed]
38. Yu, K.N. A review of Radon pollution in buildings in Hong Kong. *Build. Environ.* **1993**, *28*, 251–253. [CrossRef]
39. El-Zaher, M.A. Seasonal variation of indoor radon concentration in dwellings of Alexandria city, Egypt. *Radiat. Protect. Dosim.* **2011**, *143*, 56–62. [CrossRef] [PubMed]
40. Arvela, H.; Holmgren, O.; Reisbacka, H.; Vinha, J. Review of low-energy construction, air tightness, ventilation strategies and indoor radon: Results from Finnish houses and apartments. *Radiat. Protect. Dosim.* **2014**, *62*, 351–363. [CrossRef] [PubMed]
41. Kemski, J.; Klingel, R.; Siehl, A.; Valdivia-Manchego, M. From Radon hazard to risk prediction-based on geological maps, soil gas and indoor measurements in Germany. *Environ. Geol.* **2009**, *56*, 1269–1279. [CrossRef]
42. Kotol, M.; Rode, C.; Clausen, G.; Nielsen, T.R. Indoor environment in bedrooms in 79 Greenlandic households. *Build. Environ.* **2014**, *81*, 29–36. [CrossRef]
43. Shurgashti, S.; Rahmani, A.; Dehdashti, A.; Moeinian, K. Determination of airborne Radon and its relationship with the type of residential buildings in Damghan, Iran. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 9601–9608. [CrossRef]
44. Franco-Marina, F.; Villalba-Caloca, J.; Segovia, N.; Tavera, L. Spatial indoor Radon distribution in Mexico City. *Sci. Total Environ.* **2003**, *317*, 91–103. [CrossRef]
45. Sundal, A.V.; Henriksen, H.; Soldal, O.; Strand, T. The influence of geological factors on indoor Radon concentrations in Norway. *Sci. Total Environ.* **2004**, *328*, 41–53. [CrossRef] [PubMed]
46. Karpińska, M.; Mnich, Z.; Kapała, J. Seasonal changes in Radon concentrations in buildings in the region of northeastern Poland. *J. Environ. Radioact.* **2004**, *77*, 101–109. [CrossRef] [PubMed]
47. Zalewski, M.; Karpińska, M.; Mnich, Z.; Kapała, J. Radon concentrations in buildings in the north-eastern region of Poland. *J. Environ. Radioact.* **1998**, *40*, 147–154. [CrossRef]
48. Cosma, C.; Cucoş-Dinu, A.; Papp, B.; Begy, R.; Sainz, C. Soil and building material as main sources of indoor Radon in Bâiţa-ştei Radon prone area (Romania). *J. Environ. Radioact.* **2013**, *116*, 174–179. [CrossRef] [PubMed]
49. Yarmoshenko, I.; Malinovsky, G.; Vasilyev, A.; Onishchenko, A. Seasonal variation of Radon concentrations in russian residential high-rise buildings. *Atmos* **2021**, *12*, 930. [CrossRef]
50. Pol, R.; Rodríguez, R.; Quindos, L.; Fuente, I. Mitigation Techniques for Interior Radon in Refurbishment Work in High Radiation Areas of Galicia: An Experimental Model to Test Building Solutions. *Civ. Environ. Eng.* **2021**, *17*, 485–499. [CrossRef]
51. Rizo-Maestre, C.; Echarri-Iribarren, V.; Prado-Govea, R.; Pujol-López, F. Radon gas as an indicator for air quality control in buried industrial architecture: Rehabilitation of the old Británica warehouses in alicante for a tourist site. *Sustainability* **2019**, *11*, 4692. [CrossRef]
52. Barros-Dios, J.M.; Ruano-Ravina, A.; Gastelu-Iturri, J.; Figueiras, A. Factors underlying residential radon concentration: Results from Galicia, Spain. *Environ. Res.* **2007**, *103*, 185–190. [CrossRef]
53. Tell, I.; Bensryd, I.; Rylander, L.; Jönsson, G.; Daniel, E. Geochemistry and ground permeability as determinants of indoor Radon concentrations in southernmost Sweden. *Appl. Geochem.* **1994**, *9*, 647–655. [CrossRef]
54. Wu, P.-Y.; Johansson, T.; Sandels, C.; Mangold, M.; Mjörnell, K. Indoor Radon interval prediction in the Swedish building stock using machine learning. *Build. Environ.* **2023**, *245*, 110879. [CrossRef]

55. Tuia, D.; Kanevski, M. Indoor Radon distribution in Switzerland: Lognormality and extreme value theory. *J. Environ. Radioact.* **2008**, *99*, 649–657. [CrossRef] [PubMed]
56. Appleton, J.D.; Miles, J.C.H. A statistical evaluation of the geogenic controls on indoor Radon concentrations and Radon risk. *J. Environ. Radioact.* **2010**, *101*, 799–803. [CrossRef] [PubMed]
57. Denman, A.R.; Crockett, R.G.M.; Groves-Kirkby, C.J. An assessment of the effectiveness of UK building regulations for new homes in Radon Affected Areas. *J. Environ. Radioact.* **2018**, *192*, 166–171. [CrossRef] [PubMed]
58. Gunby, J.A.; Darby, S.C.; Miles, J.C.; Green, B.M.; Cox, D.R. Factors affecting indoor Radon concentrations in the United Kingdom. *Health Phys.* **1993**, *64*, 2–12. [CrossRef] [PubMed]
59. Smith, B.J.; Field, R.W. Effect of housing factor and surficial uranium on the spatial prediction of residential Radon in Iowa. *Environmetrics* **2007**, *18*, 481–497. [CrossRef]
60. Shi, X.; Hoftiezer, D.J.; Duell, E.J.; Onega, T.L. Spatial association between residential Radon concentration and bedrock types in New Hampshire. *Environ. Geol.* **2006**, *51*, 65–71. [CrossRef]
61. Apte, M.G.; Price, P.N.; Nero, A.V.; Revzan, K.L. Predicting New Hampshire indoor Radon concentrations from geologic information and other covariates. *Environ. Geol.* **1999**, *37*, 181–194. [CrossRef]
62. Price, P.N.; Nero, A.V.; Gelman, A. Bayesian prediction of mean indoor Radon concentrations for Minnesota counties. *Health Phys.* **1996**, *71*, 922–936. [CrossRef]
63. Nero, A.V.; Schwehr, M.B.; Nazaroff, W.W.; Revzan, K.L. Distribution of airborne Radon-222 concentrations in US homes. *Science* **1986**, *234*, 992–997. [CrossRef]
64. Dai, D.; Neal, F.B.; Diem, J.; Deocampo, D.M.; Stauber, C.; Dignam, T. Confluent impact of housing and geology on indoor Radon concentrations in Atlanta, Georgia, United States. *Sci. Total Environ.* **2019**, *668*, 500–511. [CrossRef]
65. Safarov, A.; Safarov, A.; Khasanov, S.; Umirzakov, E.; Proshad, R.; Suvanova, S.; Muminov, M. Evaluation of Radon hazards at the rural settlements of Uzbekistan. *Environ. Monit. Assess.* **2023**, *195*, 915. [CrossRef] [PubMed]
66. Bucci, S.; Pratesi, G.; Viti, M.L.; Pantani, M.; Bochicchio, F.; Venoso, G. Radon in workplaces: First results of an extensive survey and comparison with Radon in homes. *Radiat. Prot. Dosim.* **2011**, *145*, 202–205. [CrossRef] [PubMed]
67. Carelli, V.; Bianco, V.; Cordedda, C.; Ferrigno, G.; Carpentieri, C.; Bochicchio, F. A national survey on Radon concentration in underground inspection rooms and in buildings of a telephone company: Methods and first results. *Radiat. Meas.* **2009**, *44*, 1058–1063. [CrossRef]
68. Rossetti, M.; Esposito, M. Radon levels in undergroundworkplaces: A map of the italian regions. *Radiat. Prot. Dosim.* **2015**, *164*, 392–397. [CrossRef] [PubMed]
69. Trevisi, R.; Orlando, C.; Orlando, P.; Amici, M.; Simeoni, C. Radon levels in underground workplaces—Results of a nationwide survey in Italy. *Radiat. Meas.* **2012**, *47*, 178–181. [CrossRef]
70. Sesana, L.; Polla, G.; Facchini, U.; De Capitani, L. Radon-prone areas in the Lombard plain. *J. Environ. Radioact.* **2005**, *82*, 51–62. [CrossRef]
71. Bochicchio, F.; Campos Venuti, G.; Nuccetelli, C.; Piermattei, S.; Risica, S.; Tommasino, L.; Torri, G. Results of the representative Italian national survey on Radon indoors. *Health Phys.* **1996**, *71*, 741–748. [CrossRef]
72. Sachs, H.M.; Hernandez, T.L.; Ring, J.W. Regional geology and Radon variability in buildings. *Environ. Int.* **1982**, *8*, 97–103. [CrossRef]
73. Ennemoser, O.; Giacomuzzi, S.M.G.; Brunner, P.; Schneider, P.; Stingl, V.; Purtscheller, F.; Ambach, W. Radon measurements in soil to predict indoor Radon concentrations in new buildings in an area with unusually high Radon levels. *Sci. Total Environ.* **1995**, *162*, 209–213. [CrossRef]
74. Sarkheil, H.; Shirkhani, D.; Azimi, Y.; Talebi, A.; Rahbari, S. Fuzzy Radon hazard index assessment for stochastic environmental health risk evaluation of urban scale building. *Stoch. Environ. Res. Risk Assess.* **2023**, *37*, 3493–3515. [CrossRef]
75. Bochicchio, F.; CamposVenuti, G.; Piermattei, S.; Nuccetelli, C.; Risica, S.; Tommasino, L.; Torri, G.; Magnoni, M.; Agnesod, G.; Sgorbati, G.; et al. Annual average and seasonal variations of residential Radon concentration for all the Italian Regions. *Radiat. Meas.* **2005**, *40*, 686–694. [CrossRef]
76. Keller, G.; Hoffmann, B.; Feigenspan, T. Radon permeability and Radon exhalation of building materials. *Sci. Total Environ.* **2001**, *272*, 85–89. [CrossRef] [PubMed]
77. Richter, M.; Jann, O.; Kemski, J.; Schneider, U.; Krocker, C.; Hoffmann, B. Determination of Radon exhalation from construction materials using VOC emission test chambers. *Indoor Air* **2013**, *23*, 397–405. [CrossRef] [PubMed]
78. Mustonen, R. Natural radioactivity in and Radon exhalation from finnish building materials. *Health Phys.* **1984**, *46*, 1195–1203. [CrossRef] [PubMed]
79. Ingersoll, J.G. A survey of radionuclide contents and Radon emanation rates in building materials used in the U.S. *Health Phys.* **1983**, *45*, 363–368. [CrossRef] [PubMed]
80. Petropoulos, N.P.; Anagnostakis, M.J.; Simopoulos, S.E. Photon attenuation, natural radioactivity content and Radon exhalation rate of building materials. *J. Environ. Radioact.* **2002**, *61*, 257–269. [CrossRef] [PubMed]
81. Chen, J.; Rahman, N.M.; Atiya, I.A. Radon exhalation from building materials for decorative use. *J. Environ. Radioact.* **2010**, *101*, 317–322. [CrossRef] [PubMed]

82. Frutos, B.; Martín-Consuegra, F.; Alonso, C.; Perez, G.; Peón, J.; Ruano-Ravina, A.; Barros, J.M.; Santorun, A.M. Inner wall filler as a singular and significant source of indoor Radon pollution in heritage buildings: An exhalation method-based approach. *Build. Environ.* **2021**, *201*, 108005. [CrossRef]
83. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources and Effects of Ionising Radiation. *Report to the General Assembly.* 2000. Available online: https://www.unscear.org/docs/publications/2000/UNSCEAR_2000_Report_Vol.I.pdf (accessed on 29 October 2023).
84. Risica, S.; Bolzan, C.; Nuccetelli, C. Radioactivity in building materials: Room model analysis and experimental methods. *Sci. Total Envrion.* **2001**, *272*, 119–126. [CrossRef]
85. Nazaroff, W.W.; Nero, A.V. *Radon and Its Decay Products in Indoor Air*; John Wiley and Sons Inc.: Hoboken, NJ, USA, 1988; ISBN 0-471-62810-7.
86. Lv, L.; He, Z.; Qiu, S.; Tang, Q. Evaluation and measurement methods for the surface Radon exhalation rate of buildings. *Indoor Built Environ.* **2022**, *31*, 2378–2385. [CrossRef]
87. Stoulos, S.; Manolopoulou, M.; Papastefanou, C. Assessment of natural radiation exposure and Radon exhalation from building materials in Greece. *J. Environ. Radioact.* **2003**, *69*, 225–240. [CrossRef] [PubMed]
88. Yu, K.N.; Chan, T.F.; Young, E.C. The variation of Radon exhalation rates from building surfaces of different ages. *Health Phys.* **1995**, *68*, 716–718. [CrossRef] [PubMed]
89. Chen, C.-J.; Weng, P.-S.; Chu, T.-C. Radon exhalation rate from various building materials. *Health Phys.* **1993**, *64*, 613–619. [CrossRef] [PubMed]
90. Righi, S.; Bruzzi, L. Natural radioactivity and Radon exhalation in building materials used in Italian dwellings. *J. Environ. Radioact.* **2006**, *88*, 158–170. [CrossRef] [PubMed]
91. Misdaq, M.A.; Ezzahery, H.; Lamine, J. Influence of the building material and ventilation rate on the concentration of Radon, thoron and their progenies in dwelling rooms using SSNTD and Monte Carlo simulation. *J. Radioanalyt. Nucl. Chem.* **2022**, *252*, 67–74. [CrossRef]
92. Di Carlo, C.; Maiorana, A.; Ampollini, M.; Antignani, S.; Caprio, M.; Carpentieri, C.; Bochicchio, F. Models of Radon exhalation from building structures: General and case-specific solutions. *Sci. Total Environ.* **2023**, *885*, 163800. [CrossRef]
93. Kumar, A.; Chauhan, R.P.; Joshi, M.; Sahoo, B.K. Modeling of indoor Radon concentration from Radon exhalation rates of building materials and validation through measurements. *J. Environ. Radioact.* **2014**, *127*, 50–55. [CrossRef]
94. Girault, F.; Perrier, F. Estimating the importance of factors influencing the Radon-222 flux from building walls. *Sci. Total Environ.* **2012**, *433*, 247–263. [CrossRef]
95. Font, L.; Baixeras, C. The RAGENA dynamic model of radon generation, entry and accumulation indoors. *Sci. Total Environ.* **2003**, *307*, 55–69. [CrossRef]
96. Stajic, J.M.; Nikezic, D. Measurement of Radon exhalation rates from some building materials used in Serbian construction. *J. Radioanalyt. Nucl. Chem.* **2015**, *303*, 1943–1947. [CrossRef]
97. Hassan, N.M.; Tokonami, S.; Fukushi, M. A simple technique for studying the dependence of Radon and thoron exhalation rate from building materials on absolute humidity. *J. Radioanalyt. Nucl. Chem.* **2011**, *287*, 185–191. [CrossRef]
98. Nunes, L.J.R.; Curado, A.; Lopes, S.I. The Relationship between Radon and Geology: Sources, Transport and Indoor Accumulation. *Appl. Sci.* **2023**, *13*, 7460. [CrossRef]
99. Bruno, R.C. Sources of indoor Radon in houses: A review. *J. Air Pollut. Control Assoc.* **1983**, *33*, 105–109. [CrossRef]
100. Borgoni, R. A quantile regression approach to evaluate factors influencing residential indoor Radon concentration. *Environ. Model. Assess.* **2011**, *16*, 239–250. [CrossRef]
101. Buchli, R.; Burkart, W. Influence of subsoil geology and construction technique on indoor air 222Rn levels in 80 houses of the central Swiss Alps. *Health Phys.* **1989**, *56*, 423–429. [CrossRef] [PubMed]
102. Lévesque, B.; Gauvin, D.; McGregor, R.G.; Martel, R.; Gingras, S.; Dontigny, A.; Walker, W.B.; Lajoie, P.; Létourneau, E. Radon in residences: Influences of geological and housing characteristics. *Health Phys.* **1997**, *72*, 907–914. [CrossRef] [PubMed]
103. Borgoni, R.; De Francesco, D.; De Bartolo, D.; Tzavidis, N. Hierarchical modeling of indoor Radon concentration: How much do geology and building factors matter? *J. Environ. Radioact.* **2014**, *138*, 227–237. [CrossRef]
104. Smith, L.; Voutchkov, M. Assessment of radon levels in drinking water Wells in St. Catherine, Jamaica. *J. Health Pollut.* **2017**, *7*, 31–37. [CrossRef]
105. Horton, T. *Nationwide Occurrence of Radon and Other Natural Radioactivity in Public Water Supplies*; U.S. Department of Energy: Washington, DC, USA, 1985. [CrossRef]
106. Kahlos, H.; Asikainen, M. Internal radiation doses from radioactivity of drinking water in Finland. *Health Phys.* **1980**, *39*, 108–111. [PubMed]
107. Cothern, C.R.; Lappenbusch, W.L.; Michel, J. Drinking-water contribution to natural background radiation. *Health Phys.* **1986**, *50*, 33–47. [CrossRef]
108. Collignan, B.; Powaga, E. Impact of ventilation systems and energy savings in a building on the mechanisms governing the indoor Radon activity concentration. *J. Environ. Radioact.* **2019**, *196*, 268–273. [CrossRef] [PubMed]
109. Baltrenas, P.; Grubliauskas, R.; Danila, V. Seasonal variation of indoor Radon concentration levels in different premises of a university building. *Sustainability* **2020**, *12*, 6174. [CrossRef]

110. Rydock, J.P.; Næss-Rolstad, A.; Brunsell, J.T. Diurnal variations in Radon concentrations in a school and office: Implications for determining Radon exposure in day-use buildings. *Atmos. Environ.* **2001**, *35*, 2921–2926. [CrossRef]
111. Hunter, N.; Howarth, C.B.; Miles, J.C.H.; Muirhead, C.R. Year-to-year variations in radon levels in a sample of UK houses with the same occupants. *Radioact. Environ.* **2005**, *7*, 438–447. [CrossRef]
112. Cavallo, A.; Gadsby, K.; Reddy, T.A. Comparison of natural and forced ventilation for Radon mitigation in houses. *Environ. Int.* **1996**, *22*, 1073–1078. [CrossRef]
113. Robinson, A.L.; Sextro, R.G. Radon entry into buildings driven by atmospheric pressure fluctuations. *Environ. Sci. Technol.* **1997**, *31*, 1742–1748. [CrossRef]
114. Riley, W.J.; Robinson, A.L.; Gadgil, A.J.; Nazaroff, W.W. Effects of variable wind speed and direction on Radon transport from soil into buildings: Model development and exploratory results. *Atmos. Environ.* **1999**, *33*, 2157–2168. [CrossRef]
115. Marley, F. Investigation of the influences of atmospheric conditions on the variability of Radon and Radon progeny in buildings. *Atmos. Environ.* **2001**, *35*, 5347–5360. [CrossRef]
116. Schubert, M.; Musolff, A.; Weiss, H. Influences of meteorological parameters on indoor Radon concentrations (222Rn) excluding the effects of forced ventilation and Radon exhalation from soil and building materials. *J. Environ. Radioact.* **2018**, *192*, 81–85. [CrossRef]
117. Winkler, R.; Ruckerbauer, F.; Bunzl, K. Radon concentration in soil gas: A comparison of the variability resulting from different methods, spatial heterogeneity and seasonal fluctuations. *Sci. Total Environ.* **2001**, *272*, 273–282. [CrossRef]
118. Yarmoshenko, I.; Zhukovsky, M.; Onishchenko, A.; Vasilyev, A.; Malinovsky, G. Factors influencing temporal variations of Radon concentration in high-rise buildings. *J. Environ. Radioact.* **2021**, *232*, 106575. [CrossRef] [PubMed]
119. Collins, M.; Dempsey, S. Residential energy efficiency retrofits: Potential unintended consequences. *J. Environ. Plan Manag.* **2019**, *62*, 2010–2025. [CrossRef]
120. Niculita-Hirzel, H. Latest trends in pollutant accumulations at threatening levels in energy-efficient residential buildings with and without mechanical ventilation: A review. *Int. J. Environ. Res. Public Health* **2022**, *19*, 3538. [CrossRef] [PubMed]
121. Wang, C.; Wang, J.; Norbäck, D. A Systematic Review of Associations between Energy Use, Fuel Poverty, Energy Efficiency Improvements and Health. *Int. J. Environ. Res. Public Health* **2022**, *19*, 7393. [CrossRef] [PubMed]
122. Yang, S.; Pernot, J.G.; Jörin, C.H.; Niculita-Hirzel, H.; Perret, V.; Licina, D. Radon investigation in 650 energy efficient dwellings in western switzerland: Impact of energy renovation and building characteristics. *Atmosphere* **2019**, *10*, 777. [CrossRef]
123. Pampuri, L.; Caputo, P.; Valsangiacomo, C. Effects of buildings' refurbishment on indoor air quality. Results of a wide survey on Radon concentrations before and after energy retrofit interventions. *Sust. Cities Soc.* **2018**, *42*, 100–106. [CrossRef]
124. Burghele, B.D.; Botoș, M.; Beldean-Galea, S.; Cucoș, A.; Catalina, T.; Dicu, T.; Dobrei, G.; Florică, Ș.; Istrate, A.; Lupulescu, A.; et al. Comprehensive survey on Radon mitigation and indoor air quality in energy efficient buildings from Romania. *Sci. Total Environ.* **2021**, *751*, 141858. [CrossRef]
125. McGrath, J.A.; Aghamolaei, R.; O'Donnell, J.; Byrne, M.A. Factors influencing Radon concentration during energy retrofitting in domestic buildings: A computational evaluation. *Build. Environ.* **2021**, *194*, 107712. [CrossRef]
126. Du, L.; Leivo, V.; Prasauskas, T.; Täubel, M.; Martuzevicius, D.; Haverinen-Shaughnessy, U. Effects of energy retrofits on indoor air quality in multifamily buildings. *Indoor Air* **2019**, *29*, 686–697. [CrossRef]
127. Peake, R.T. Radon and Geology in the United States. *Radiat. Prot. Dosim.* **1988**, *24*, 173–178. [CrossRef]
128. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). *Sources-to-Effects Assessment for Radon in Homes and Workplaces*; Report to the General Assembly; United Nations: New York, NY, USA, 2006; Available online: https://www.unscear.org/docs/publications/2006/UNSCEAR_2006_Annex-E-CORR.pdf (accessed on 29 October 2023).
129. Tokonami, S.; Sun, Q.; Akiba, S.; Zhuo, W.; Furukawa, M.; Ishikawa, T.; Hou, C.; Zhang, S.; Narazaki, Y.; Ohji, B.; et al. Radon and thoron exposures for cave residents in Shanxi and Shaanxi provinces. *Radiat. Res.* **2004**, *162*, 390–396. [CrossRef] [PubMed]
130. Ishikawa, T.; Tokonami, S.; Nemeth, C. Calculation of dose conversion factors for thoron decay products. *J. Radiol. Protect.* **2007**, *27*, 447–456. [CrossRef] [PubMed]
131. Gaskin, J.; Coyle, D.; Whyte, J.; Birkett, N.; Krewksi, D. A cost effectiveness analysis of interventions to reduce residential Radon exposure in Canada. *J. Environ. Manag.* **2019**, *247*, 449–461. [CrossRef] [PubMed]
132. Haucke, F. The cost effectiveness of Radon mitigation in existing German dwellings—A decision theoretic analysis. *J. Environ. Manag.* **2010**, *91*, 2263–2274. [CrossRef] [PubMed]
133. Denman, A.R.; Phillips, P.S.; Tornberg, R. The costs and benefits of radon remediation programmes in existing homes: Case study of action level selection. *J. Environ. Radioact.* **2002**, *62*, 17–27. [CrossRef] [PubMed]
134. Khan, S.M.; Gomes, J.; Krewski, D.R. Radon interventions around the globe: A systematic review. *Heliyon* **2019**, *5*, e01737. [CrossRef]
135. Groves-Kirkby, C.J.; Denman, A.R.; Phillips, P.S.; Crockett, R.G.M.; Woolridge, A.C.; Tornberg, R. Radon mitigation in domestic properties and its health implications—A comparison between during-construction and post-construction Radon reduction. *Environ. Int.* **2006**, *32*, 435–443. [CrossRef]
136. Vázquez, B.F.; Adán, M.O.; Poncela, L.S.Q.; Fernandez, C.S.; Merino, I.F. 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.* **2011**, *102*, 378–385. [CrossRef]
137. Arvela, H. Radon mitigation in blocks of flats. *Sci. Total Environ.* **2001**, *272*, 137. [CrossRef]

138. Ennemoser, O.; Oberdorfer, E.; Brunner, P.; Schneider, P.; Purtscheller, F.; Stingl, V.; Ambach, W. Mitigation of indoor radon in an area with unusually high radon concentrations. *Health Phys.* **1995**, *69*, 227–233. [CrossRef]
139. Boardman, C.R.; Glass, S.V. Basement radon entry and stack driven moisture infiltration reduced by active soil depressurization. *Build. Environ.* **2015**, *85*, 220–232. [CrossRef]
140. Paridaens, J.; de Saint-Georges, L.; Vanmarcke, H. Mitigation of a radon-rich Belgian dwelling using active sub-slab depressurization. *J. Environ. Radioact.* **2005**, *79*, 25–37. [CrossRef] [PubMed]
141. Groves-Kirkby, C.J.; Denman, A.R.; Phillips, P.S.; Tornberg, R.; Woolridge, A.C.; Crockett, R.G.M. Domestic radon remediation of U.K. dwellings by sub-slab depressurisation: Evidence for a baseline contribution from constructional materials. *Environ. Int.* **2008**, *34*, 428–436. [CrossRef] [PubMed]
142. Henschel, D.B. Analysis of radon mitigation techniques used in existing US houses. *Radiat. Protect. Dosim.* **1994**, *56*, 21–27. [CrossRef]
143. Holmgren, O.; Arvela, H. Assessment of current techniques for reduction of indoor radon concentration in existing and new houses in European countries. *Environ. Sci.* **2012**, *44*, 1–102. Available online: https://www.julkari.fi/bitstream/handle/10024/124855/stuk-a251.pdf (accessed on 29 October 2023).
144. Marley, F.; Phillips, P.S. Investigation of the potential for radon mitigation by operation of mechanical systems affecting indoor air. *J. Environ. Radioact.* **2001**, *54*, 205–219. [CrossRef]
145. Rahman, N.M.; Tracy, B.L. Radon control systems in existing and new construction: A review. *Radiat. Protect. Dosim.* **2009**, *135*, 243–255. [CrossRef]
146. Valmari, T.; Arvela, H.; Reisbacka, H.; Holmgren, O. Radon measurement and mitigation activity in Finland. *Radiat. Protect. Dosim.* **2014**, *160*, 18–21. [CrossRef]
147. Wang, F.; Ward, I.C. A case study on radon remedial measures in a family dwelling. *Health Phys.* **1997**, *73*, 787–793. [CrossRef]
148. Yasuoka, Y.; Ishikawa, T.; Tokonami, S.; Takahashi, H.; Sorimachi, A.; Shinogi, M. Radon mitigation using an air cleaner. *J. Radioanal. Nucl. Chem.* **2009**, *279*, 885–891. [CrossRef]
149. Lowe, S.; Pettenato, R. Reduction of indoor Radon by air cleaning—A case study. *J. Environ. Eng.* **2000**, *126*, 1125. [CrossRef]
150. Rajala, M.; Janka, K.; Lehtimaki, M.; Kulmala, V.; Graeffe, G.; Keskinen, J. The control of radon progeny by air treatment devices. *Sci. Total Environ.* **1985**, *45*, 493–498. [CrossRef] [PubMed]
151. Rydock, J.P.; Næss-Rolstad, A.; Brunsell, J.T. Effectiveness of radon mitigation measures in 12 houses 10 years after implementation. *Indoor Built Environ.* **2002**, *11*, 38–43. [CrossRef]
152. Naismith, S.P.; Miles, J.C.H.; Scivyer, C.R. The influence of house characteristics on the effectiveness of radon remedial measures. *Health Phys.* **1998**, *75*, 410–416. [CrossRef] [PubMed]
153. Long, S.; Fenton, D.; Cremin, M.; Morgan, A. The effectiveness of radon preventive and remedial measures in Irish homes. *J. Radiol. Prot.* **2013**, *33*, 141–149. [CrossRef]
154. Chen, J.; Ly, J.; Schroth, E.; Hnatiuk, S.; Frenette, E.; Blain, M.-F. Radon diffusion coefficients of vapour barrier membranes used in Canadian building construction. *Radiat. Environ. Biophys.* **2009**, *48*, 153–158. [CrossRef]
155. Tsapalov, A.; Kovler, K. Revisiting the concept for evaluation of Radon protective properties of building insulation materials. *Build. Environ.* **2016**, *95*, 182–188. [CrossRef]
156. Jiránek, M.; Kačmaříková, V. Radon diffusion coefficients and Radon resistances of waterproofing materials available on the building market. *J. Environ. Radioact.* **2019**, *208–209*, 106019. [CrossRef]
157. Scivyer, C.R. Radon protection for new buildings: A practical solution from the UK. *Sci. Total Environ.* **2001**, *272*, 91–96. [CrossRef]
158. Gao, X.F.; Tam, C.M.; Gao, W.Z. Polymer cement plaster to prevent Radon gas contamination within concrete building structures. *Build. Environ.* **2002**, *37*, 357–361. [CrossRef]
159. Barazza, F.; Murith, C.; Palacios, M.; Gfeller, W.; Christen, E. A national survey on Radon remediation in Switzerland. *J. Radiol. Protect.* **2018**, *38*, 25–33. [CrossRef] [PubMed]