

## Review

# The Relationship between Radon and Geology: Sources, Transport and Indoor Accumulation

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**Abstract:** This review study examines the relationship between radon and geology, including its origins, transmission, and accumulation, as well as its impact on human health and mitigation strategies. The decay of uranium and thorium produces radon, a radioactive gas. Its concentration in the environment fluctuates based on local geology, soil permeability, climate, and terrain, as well as regional, seasonal, and daily meteorological conditions. Exposure to radon indoors is associated with an increased risk of lung cancer, making it a significant public health concern. Measuring radon concentrations in indoor environments is essential for identifying high-risk areas and devising effective mitigation strategies, such as ventilation, fissure sealing, and exhaust installation. The need for greater knowledge of regional and seasonal fluctuations in radon concentration, as well as the development of more effective and cost-effective measuring and mitigation strategies, has implications for future research. To influence public health policies and practices, more research on the long-term health effects of radon exposure is required. The focus of public health policy should be on increasing awareness of the dangers associated with radon exposure, supporting regular measurement and monitoring of radon concentrations in indoor areas, and encouraging the adoption of effective mitigation techniques. When selecting construction sites, urban planning regulations and building codes should consider the local geology and radon levels in the soil.

**Keywords:** radon; geology; indoor environment; mitigation measures; public health



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## 1. Introduction

Radon ( $^{222}\text{Rn}$ ) is a colourless, odourless, and tasteless radioactive gas, primarily originating from the decay of uranium, and present in rocks, soil, and water [1]. The relationship between radon and geology is a crucial topic for understanding the sources, transport, and accumulation of this gas, and for assessing its potential risks to human health, as well as for developing effective mitigation and monitoring strategies for  $^{222}\text{Rn}$  [2]. Geological factors are determining factors in the production and distribution of radon, and the presence and concentration of uranium ( $^{238}\text{U}$ ) will determine the amount of radon emitted [3]. On the other hand, local geological characteristics, such as rock permeability, soil porosity, geological structure, and topography, directly affect the transport and accumulation of radon [4,5]. These factors can interact in complex ways, resulting in different patterns of radon distribution and concentration [6]. Understanding these relationships is fundamental for identifying areas of higher risk and implementing protective measures [7].

Long-term radon exposure is linked to the risk of lung cancer occurrence, a significant health hazard that claims countless lives worldwide each year. This correlation highlights the importance of continuously assessing and monitoring radon levels, particularly in residential and occupational settings. Due to the invisible nature of this gas, as well as its ability to accumulate undetected in enclosed spaces, there is an urgent need for vigilant surveillance, prompt mitigation strategies, and public education regarding the potential risks. Through these concerted efforts, the public health challenge posed by radon exposure can be effectively addressed, reducing its impact on lung cancer incidence rates and ultimately improving the health and longevity of communities [8–11]. Understanding the relationship between radon and geology allows the development of risk maps and the identification of areas that require monitoring and specific interventions [9,12,13].

This review article explores the relationship between radon and geology, with a focus on sources, transport, and indoor radon accumulation. It also discusses the impacts on human health through an analysis of the most relevant studies published in the past decades. The objectives of this review are to examine the radioactive decay mechanisms that cause radon to be released, discuss regional and seasonal fluctuations in radon concentration, and assess the health concerns of radon exposure. The methods for measuring radon levels in rocks and soils are examined, and mitigation measures, such as ventilation, crack sealing, and exhaust system installation, to lower radon exposure in indoor spaces are studied. Finally, the ramifications for future studies and public health regulations are discussed.

## 2. The Origin of Radon

### 2.1. Radioactive Decay

Radon is generated from the decay of radioactive elements such as  $^{238}\text{U}$  and thorium ( $^{232}\text{Th}$ ), and their descendants [14]. The primary sources of  $^{222}\text{Rn}$  are  $^{238}\text{U}$ ,  $^{235}\text{U}$  and  $^{232}\text{Th}$ , which are naturally found in rocks, soils and water [15]. Radioactive decay is a natural process by which an unstable nucleus of an element transforms into a more stable nucleus, releasing particles and energy in the process [16].  $^{238}\text{U}$  is the most common isotope of uranium, comprising approximately 99.3% of the uranium found in the earth's crust [17,18]. It decays through a series of radioactive decays, forming a chain of daughter elements. One of the products of this chain is radium ( $^{226}\text{Ra}$ ), which through alpha decay ( $^{226}\text{Ra}$  emits an alpha particle composed of two protons and two neutrons) transforms into  $^{222}\text{Rn}$  [19].  $^{222}\text{Rn}$  is the most common and significant isotope in terms of human exposure and health risk [20]. The decay chain of  $^{238}\text{U}$  includes the main radioactive elements  $^{234}\text{Th}$ ,  $^{234}\text{Pa}$ ,  $^{234}\text{U}$ ,  $^{230}\text{Th}$  and  $^{226}\text{Ra}$ , from which  $^{222}\text{Rn}$  originates [21].  $^{235}\text{U}$  is another isotope of uranium, although it is much less common than  $^{238}\text{U}$ , representing only about 0.7% of uranium in the earth's crust [22]. It also decays through a series of radioactive decays, forming a chain of daughter elements. However, the amount of  $^{222}\text{Rn}$  generated from the decay of  $^{235}\text{U}$  is less than the amount generated from  $^{238}\text{U}$ , due to its lower abundance and longer decay chain [23].  $^{232}\text{Th}$  is a radioactive element naturally found in the earth's crust, and also decays through a series of radioactive decays, forming a chain of daughter elements [24]. One of the products of this chain is  $^{224}\text{Ra}$ , which decays to form  $^{220}\text{Rn}$ , also known as thoron [25]. The decay chain of  $^{232}\text{Th}$  includes the main radioactive elements  $^{228}\text{Ra}$ ,  $^{228}\text{Ac}$ ,  $^{228}\text{Th}$  and  $^{224}\text{Ra}$ , from which  $^{220}\text{Rn}$  originates [26]. However, although  $^{220}\text{Rn}$  is released during the decay of  $^{232}\text{Th}$ , its short half-life (approximately 55 s) limits its contribution to radon exposure compared with  $^{222}\text{Rn}$  [27]. Being a noble gas,  $^{222}\text{Rn}$  moves freely through the pores and fissures of the soil and rocks, in contrast to other decay products, which are solids and remain fixed in place [28]. Once released into the environment,  $^{222}\text{Rn}$  continues to decay into a series of daughter radioactive elements, such as  $^{218}\text{Po}$ ,  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$ , which are also radioactive [29]. The decay of  $^{222}\text{Rn}$  and its subsequent decay products emits alpha, beta and gamma radiation [30].

## 2.2. Rocks and Soil Migration Factors

### 2.2.1. Permeability of Soil and Rocks

Permeability is the ability of soil and rocks to allow the passage of water and gases [31]. Soils and rocks with higher permeability, such as sandstones and limestones, have larger pores and fissures, allowing radon to move more easily [32]. On the other hand, soils and rocks with low permeability, such as clays and shales, tend to retain radon and limit its mobility [33]. The permeability of the soil and rocks plays a crucial role in the movement of radon through the environment and can have a significant impact on the concentration of radon in indoor environments [34]. In areas with high permeability, radon can seep through the soil and enter buildings, increasing the risk of exposure [35]. In contrast, in areas with low permeability, radon can become trapped in the soil and not reach indoor environments, reducing the risk of exposure [36]. The permeability of soil and rocks in a given area is an important factor when identifying high-risk areas and developing effective mitigation strategies [37]. Therefore, the combined measurements of soil permeability and concentration of uranium and thorium in rocks and soils allow assessment of the concentration of radon and the risk of exposure in a particular region [38]. For example, granitic rocks, despite exhibiting low porosity, may display high permeability if highly fractured. On the other hand, volcanic rocks can have high porosity due to the presence of vesicles, yet their permeability is often constrained by a lack of connectivity among these pores [39,40]. Clays, siltstones, and mudstones typically present low permeability, largely owing to the small size of their pores and a lack of interconnectivity among them [41]. Lastly, limestones can exhibit a wide range in permeability, from very low in microcrystalline limestones to very high in fractured limestones or those with substantial intergranular porosity [42,43]. There are several relevant studies about this subject. One of the first research studies, which was published by Ball et al. (1991), is a comprehensive and seminal review about radon's behaviour in the geological environment [32]. The authors explored the general geochemistry of radon, highlighted the factors that control its emanation from minerals and rocks into disperse phases and outlined the importance of the permeability of the host rock and soil in the process of radon diffusion. The study emphasises that the emanation of radon depends not only on the uranium concentration of the source, which acts as the progenitor of radon in the decay series, but also significantly on the nature of the host mineralogy and the permeability of the host rock and soil. The permeability of these hosts is critical as it determines how easily radon can move and diffuse through the rock or soil. A rock or soil with high permeability provides easier pathways for radon to escape, thus enhancing its diffusion. These authors underlined the role of weather, which can profoundly affect the concentration of radon in soil gas. However, they noted that variations due to the geological substrate are often greater, which underscores the overarching importance of geology in radon behaviour. The authors concluded the study by presenting guidelines to identify areas of high radon emanation, which is especially relevant given that radon becomes a problem when it collects in buildings and underground structures. Examples of different types of porosity are presented in the study by Šperl and Trčková (2008), and they provide valuable insights into the factors that influence the permeability of rocks, emphasizing the role of microstructure, defined in terms of pore and crack structures [44]. The permeability of porous materials is determined not only by porosity but also by the shape and arrangement of pores and the amount of clayey component. Importantly, only effective porosity, represented by interconnected open pores, influences permeability as it allows the passage of water. The influence of pore size distribution and the quantity of clayey components on permeability were underscored, necessitating their consideration when examining the relationship between porosity and permeability. The study also emphasized the importance of rock bulk and particle density. The results of laboratory tests on different types of rocks offer insights into the relationships between their basic physical properties, such as water permeability, porosity, pore size distribution, mechanical strength, and durability (Table 1). These properties are critical for predicting rock behaviour under varying environmental conditions and for determining

their potential usage. The study highlights grain size as an important factor influencing porosity and permeability. Rocks with uniform grain size are found to have higher porosity compared with poorly sorted materials of similar size, where smaller particles fill the gaps between larger particles, reducing porosity and potentially influencing permeability. This relationship between rock permeability and grain size distribution offers a new area for further study.

**Table 1.** Porosity of several lithologies (adapted from [44]).

| Lithologies     | Porosity (%) |
|-----------------|--------------|
| Arenaceous marl | 24.54–31.74  |
| Basalt          | 3.06         |
| Gneiss          | 1.21         |
| Granite         | 2.70         |
| Limestone       | 2.00–12.09   |
| Marlite         | 15.45–19.03  |
| Sandstones      | 11.95–24.94  |

### 2.2.2. Diffusion

Diffusion is the process by which radon moves from areas of higher concentration to areas of lower concentration through the pores and fissures of rocks until it reaches a uniform concentration [45]. The rate of diffusion depends on various factors, such as the size of the pores and the pressure gradients across them. As radon diffuses through rocks, it can become trapped in soil, water, or even buildings, where it can accumulate to dangerous levels [46]. The diffusion of radon is also affected by other factors, such as the temperature and moisture content of the rocks [47]. In general, higher temperatures and moisture content can increase the diffusion of radon, while lower temperatures and drier conditions can slow down its diffusion [48]. A pioneer study was presented by Nazaroff (1992) explored the factors that govern the rate at which two radon isotopes,  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$ , migrate from soil into the atmosphere, both outdoors and indoors [49]. According to the article, radon is created by the radioactive decay of radium in the first few metres of the Earth's crust, and during its brief lifetime, it can migrate into the atmosphere. As the respiratory tract's lining cells are exposed to the short-lived decay products of radon by inhalation, this poses a serious health risk. The investigation also shows that the average amount of radium in surface soils in the US is between 10 and 100  $\text{Bq}\cdot\text{kg}^{-1}$ . The amount of radon produced in a material that diffuses into the pore fluids is referred to as the emanation coefficient, which is normally about 0.2 but can vary. Radon may exist in pore air, be dissolved in pore water, and be absorbed by soil granules in soil pores. The author discovered that radon primarily migrates through soil pores via molecular diffusion, with the exception of areas near buildings. For the radioactive elements  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$ , the observed average flux densities from undisturbed soil into the atmosphere are  $0.015\text{--}0.048\text{ Bq}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  and  $1.6\text{--}1.7\text{ Bq}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , respectively. Soil is the main source of radon in the majority of structures. The study also showed that the advective flow of soil gas across building substructure penetrations is an essential part of the transport process and is influenced by weather patterns and the functioning of HVAC systems. Although the study found that advection was more important in structures with high concentrations of radon, it is unclear how much diffusion through soil pores contributes to radon entrance into buildings.

### 2.2.3. Pressure

Pressure differences in the soil and rocks can also drive the movement of radon. In general, radon tends to migrate from areas of high pressure to areas of low pressure [50]. For example, the gas pressure in the subsurface may be higher than atmospheric pressure, which causes radon to move towards the surface [51]. Pressure differences can also occur due to natural geological features such as faults, fractures, and other openings in the rock,

which can create areas of high or low pressure that affect the movement of radon [52]. The movement of radon through these pathways can be enhanced by factors such as soil moisture, temperature, and the concentration of other gases in the subsurface [53]. The migration of radon through soil and rock can be complex and difficult to predict, highlighting the importance of using multiple techniques to assess radon concentration and movement in different geological settings [54]. These interactions were comprehensively discussed by Pinault and Baubron (1997) who used the value of signal processing to interpret diurnal and semidiurnal variations in atmospheric pressure and radon concentration in soil gases [55]. The authors found that these variations could be used to estimate soil gas transport parameters, potentially providing meaningful insights into the real gas velocity. Their investigation identified two peaks in the power spectral density (PSD) of atmospheric pressure at 12 and 24 h intervals, a pattern that seems to be common on the surface of the Earth. These pressure changes allowed the researchers to calculate three soil gas transport parameters: tortuosity, the ratio of intrinsic permeability to effective porosity (the portion of porosity involved in gas transport), and the pressure gradient. The parameters  $k$  and  $n$  could be independently established when the surface gas flux was simultaneously monitored. This reliable assessment of transport parameters is made possible by the robust and representative method, which provides important details about the depth of radon sources and the time it takes for information to reach the surface when radon bursts take place at deep levels. Given that radon is present in all soils and that detecting its concentration simply calls for passive sensors that do not obstruct the rising gas column, its use as a soil gas tracer is particularly appropriate. Data on gas flux gathered in Andalusia, Spain, in connection with mineral exploration was used by the authors to test their methodology. It was discovered that the full set of transport characteristics could help interpret observed radon outbursts, which curiously, were linked to local seismic activity. Thus, their work demonstrates the potential of this method for geological research and hazard prediction.

#### 2.2.4. Other Factors

Other factors, such as the presence of groundwater, climatic factors, or topography, can also influence the mobility of radon [56–58]:

- **Groundwater:** The presence of water in the soil can act as a barrier, slowing down the migration of radon through the soil and rocks [6]. This occurs because water molecules tend to adhere to soil particles and create a film around them, which reduces the space available for gas migration [59]. However, if water is flowing through the soil or rock, it can carry dissolved radon to other areas [60]. Radon can dissolve in groundwater and be transported along with the water flow, potentially spreading the gas to other areas and increasing the risk of human exposure [61]. The concentration of radon in groundwater can vary greatly depending on the local geology and other environmental factors, and it is important to monitor the radon concentration in both groundwater and indoor air to assess the potential risk to human health [62]. Additionally, water can contribute to the accumulation of radon in indoor environments through the use of water sources such as showers and faucets, which can release radon gas into the air [63]. This was demonstrated in a recent study conducted by Ibánhez et al. (2023), who undertook an extensive survey of the Ría de Vigo catchment, a region that constitutes the most radon-prone area in the Iberian Peninsula [64]. The researchers sought to elucidate the environmental factors contributing to human exposure risk to radon during domestic water use. Their results revealed that continental waters in the area were considerably enriched in radon, with groundwater displaying levels one to two orders of magnitude higher than rivers. This was especially evident in the deeper fractured rock aquifers, where radon activity was an order of magnitude higher than in the heavily worn top regolith. Intriguingly, radon levels in the majority of the investigated waters virtually doubled during the dry season compared with the rainy season. This occurrence was related to seasonal water use, recharge cycles, and thermal convection. The authors warn that because of the high radon activity, home

use of untreated groundwater results in a cumulative effective dose of radiation that is higher than the advised limit of  $0.1 \text{ mSv} \cdot \text{y}^{-1}$ . They advise the installation of radon remediation and mitigation measures prior to the extraction of untreated groundwater into residences, particularly during the dry season, given that over 70% of this dosage is caused by indoor water degassing and subsequent radon inhalation.

- Climatic factors: Climatic conditions, such as temperature, humidity, and precipitation, also affect the transport of radon [65]. Temperature changes can affect the pressure in the soil, leading to variations in the mobility of radon [66]. Additionally, lower temperatures typically result in higher condensation, which can restrict the diffusion of radon. Soil moisture can affect the permeability and diffusion capacity of radon [67]. Wet soil can limit the mobility of radon, acting as a barrier to gas diffusion. Excessive precipitation can saturate the soil, making it difficult for radon to diffuse and increasing the likelihood that it will be transported by groundwater [7]. On the other hand, in drier climates, the diffusion of radon can be more efficient as soil moisture is lower. The research conducted by Sundal et al. (2008) investigated the influence of various meteorological parameters on soil radon levels in permeable glacial sediments in Kinsarvik (Norway), demonstrating the importance and influence of climatic and meteorological factors [68]. The authors continuously recorded soil radon concentrations, temperature, precipitation, wind speed and direction, air pressure, and soil moisture content throughout a ten-month period. The results showed that differences in air temperature had a significant seasonal and diurnal impact on soil radon concentrations. Due to temperature variations between soil air and atmospheric air, the investigation observed air movements between regions of the ice-marginal deposit at different elevations. Notably, immediate changes in air flow direction were seen when ambient air temperatures approached the average yearly air temperature. The second most significant factor influencing soil radon concentrations was found to be air pressure. Precipitation, wind speed and direction, or soil moisture, however, had no discernible influence. The research also investigated how indoor and soil radon levels varied seasonally in a glaciofluvial deposit 40 km southwest of Kinsarvik. The seasonal fluctuation patterns in the two places were correlated, which raises the possibility that the findings may also be applicable to other regions with highly permeable building ground and variations in terrain elevation.
- Topography: The topography of the terrain also influences the transport of radon [69]. The presence of slopes, hills, and depressions can affect air circulation and soil pressure, which in turn affects the mobility of radon [70]. In areas with rugged terrain, the drainage of groundwater and air circulation may be greater, resulting in lower accumulation of radon [57]. On the other hand, depressions and low-lying areas can act as traps for radon, leading to higher concentrations of the gas. Griffiths et al. (2014) highlighted the influence of atmospheric conditions and topography on radon concentration [69]. Specifically, the radon measurements at Jungfraujoch were intermittently affected by boundary-layer air brought to the station by processes including thermally driven (anabatic) mountain winds. These observations suggest the potential for topographical features and atmospheric dynamics to significantly impact radon distribution in the environment. This highlights the importance of considering the interplay of topography and atmospheric processes when assessing radon concentrations in various geographic locations.

### 2.3. Accumulation of Radon in Indoor Environments

#### 2.3.1. Radon Diffusion from the Soil

The process of radon diffusion is strongly influenced by the porosity of the soil and the permeability of rocks, both of which are crucial elements in facilitating the mobility of this gas. Soil porosity, referring to the amount of free space between grains, determines the ease with which radon can move. More porous soils allow for quicker radon diffusion. The permeability of rocks, which is the ease with which a fluid can traverse them, also

plays a significant role. Highly permeable rocks such as sandstone and limestone facilitate radon diffusion, whereas less permeable rocks such as clay and shale tend to restrict it. The diffusion coefficient, a parameter quantifying the movement of radon through these mediums, is influenced by various factors, including soil porosity, rock permeability, and soil moisture. In practical terms, dry and sandy soils generally exhibit a higher diffusion coefficient, allowing radon to move more freely, while clayey and moist soils possess a lower diffusion coefficient, thereby limiting the mobility of radon. The study by Thu and Van Thang (2020) examined the impacts of various factors on the radon emanation and diffusion coefficients [71].

These elements included temperature, grain size, moisture content, main element make-up, and soil pH. Their research revealed that grain size and moisture content had a large impact on the emanation and diffusion coefficients. The radon emission coefficient rose as particle size decreased, while the diffusion coefficient fell. However, despite fluctuations in grain size in soils with larger particle sizes, both coefficients remained mostly unchanged. The study also analysed soil particles of five different sizes and discovered that when moisture content rose, the emanation coefficient rose along with it, while the diffusion coefficient fell. Depending on the variety of grain sizes, the radon emission coefficient had consistent values at various moisture concentrations. When moisture content rose, the researchers saw a sharp rise in radon emissions from smaller grain sizes. For soil grains with a size between 0.1 and 0.5 mm, the saturation emanation coefficient ranged from 0.47 to 0.23, while the associated saturation moisture contents ranged from 16% to 4%. It is interesting that the study discovered that the soil's pH and iron concentration appeared to have a substantial impact on the radon emission coefficient. Additionally, the study's calculations for the effective diffusion coefficient agreed with those made by an earlier model. The study demonstrated that the radon diffusion coefficient exhibits Arrhenius behaviour in its temperature dependence. According to the underlying principles of diffusion, which indicate that diffusion rates rise with temperature, the diffusion coefficient also rises with temperature.

A study, from Tzortziz et al. (2003), utilized high-resolution gamma-ray spectroscopy to examine natural radioactivity, elemental concentrations, and dose rates in various rock types, predominantly from Cyprus (Table 2) [72]. The results show that samples originating from the Troodos ophiolitic complex generally contain lower radionuclide concentrations than those of sedimentary origin. The latter, particularly when combined with phosphates, carbonates, and silicates, show higher concentrations of elements in the uranium and thorium series. However, thorium, uranium, and potassium activity and elemental concentrations in the soil samples studied were found to be within normal ranges and significantly lower than those observed in other countries. The mean absorbed dose rate in air outdoors was significantly below the world-average value, implying that Cyprus's inhabitants are exposed to radiation levels considerably lower than those reported globally. However, as the study only measured outdoor dose rates, additional research is necessary to determine indoor dose rates.

Another study, presented by Borgoni et al. (2011), examines the relationship between indoor radon concentration (IRC) and geological and architectural factors, focusing on the Lombardy region of Italy. The article illustrates that differences in air pressure between a building's interior and the surrounding soil can allow radon gas to infiltrate through cracks in the foundation and other structural openings. This infiltration is affected by both geological and architectural factors. The research indicates a spatial correlation between high IRC areas and specific geological structures (Table 3). This was demonstrated through geostatistical mapping of the region, based on a 2003 indoor radon gas monitoring survey data combined with lithological and soil information. The paper acknowledges that the geological structure can influence IRC, but there may also be other unidentified spatial components affecting it. Furthermore, the granularity of geological information can influence the predictive capacity of geological classifications. The study also recognizes the influence of other factors beyond lithology and soil porosity, such as environmental

and anthropogenic influences. For instance, it found that the proximity of a building to a tectonic fault line can significantly influence IRC. This is a new finding that attempts to quantify the relationship between tectonic structures and radon flow. The results imply that differentiated construction requirements could be beneficial in large and heterogeneous regions, and that certain types of dwellings may warrant closer monitoring to reduce IRC when necessary. This study contributes to our understanding of IRC, but also highlights the need for further research, particularly in the context of higher resolution geological data.

**Table 2.** Natural radioactivity of in the samples used in the study by Tzortzis et al. (2003) [72].

| Rock Type                                                   | Concentration $\pm$ Standard Deviation (Bq·kg <sup>−3</sup> ) |                  |                  |
|-------------------------------------------------------------|---------------------------------------------------------------|------------------|------------------|
|                                                             | <sup>232</sup> Th                                             | <sup>238</sup> U | <sup>40</sup> K  |
| <i>Ophiolitic origin</i>                                    |                                                               |                  |                  |
| Asbestos mine waste tip material                            | 1.5 $\pm$ 0.1                                                 | 1.7 $\pm$ 0.1    | 20.0 $\pm$ 0.9   |
| Dunite                                                      | 1.3 $\pm$ 0.1                                                 | 1.3 $\pm$ 0.1    | 16.9 $\pm$ 0.9   |
| Gabbro                                                      | 1.8 $\pm$ 0.1                                                 | 1.5 $\pm$ 0.6    | 71.2 $\pm$ 2.9   |
| Harzburgite                                                 | 1.7 $\pm$ 0.1                                                 | 1.2 $\pm$ 0.1    | 16.2 $\pm$ 0.8   |
| Mathiatis pyrite mine tippings                              | 2.5 $\pm$ 1.1                                                 | 50.5 $\pm$ 0.6   | 31.9 $\pm$ 16.8  |
| Plagiogranite                                               | 2.8 $\pm$ 0.1                                                 | 3.0 $\pm$ 0.1    | 128.4 $\pm$ 5.0  |
| Pyroxenite                                                  | 1.8 $\pm$ 0.1                                                 | 1.1 $\pm$ 0.1    | 14.9 $\pm$ 0.7   |
| Sheeted dyke complex (diabase)                              | 2.7 $\pm$ 0.1                                                 | 2.7 $\pm$ 0.1    | 106.6 $\pm$ 4.2  |
| Troodos lower pillow lavas (oversaturated basalt)           | 2.9 $\pm$ 0.2                                                 | 5.2 $\pm$ 0.3    | 307.2 $\pm$ 11.8 |
| Troodos upper pillow lavas (olivine basalt, picrite basalt) | 3.2 $\pm$ 0.2                                                 | 2.8 $\pm$ 0.1    | 894.2 $\pm$ 34.0 |
| Wehrlite                                                    | 1.4 $\pm$ 0.1                                                 | 0.9 $\pm$ 0.1    | 13.0 $\pm$ 0.6   |
| <i>Sedimentary origin</i>                                   |                                                               |                  |                  |
| Calcareous sandstone                                        | 8.7 $\pm$ 0.3                                                 | 21.7 $\pm$ 0.6   | 53.5 $\pm$ 2.4   |
| Celestite                                                   | 2.4 $\pm$ 0.2                                                 | 56.0 $\pm$ 1.5   | 17.6 $\pm$ 1.0   |
| Chalk                                                       | 9.6 $\pm$ 0.3                                                 | 5.4 $\pm$ 0.2    | 87.0 $\pm$ 3.5   |
| Gypsum                                                      | 2.8 $\pm$ 0.2                                                 | 3.8 $\pm$ 0.1    | 20.9 $\pm$ 1.1   |
| Klavydhia, raised marine terrace deposits                   | 21.3 $\pm$ 0.7                                                | 90.3 $\pm$ 2.5   | 240.3 $\pm$ 9.5  |
| Larnaka beach deposits                                      | 14.9 $\pm$ 0.5                                                | 13.2 $\pm$ 0.5   | 127.7 $\pm$ 5.2  |
| Lemesos beach deposits                                      | 3.9 $\pm$ 0.2                                                 | 3.1 $\pm$ 0.1    | 76.1 $\pm$ 3.0   |
| Limestone                                                   | 2.1 $\pm$ 0.1                                                 | 8.3 $\pm$ 0.3    | 20.0 $\pm$ 1.0   |
| Marl (Dhali area)                                           | 10.5 $\pm$ 0.4                                                | 19.1 $\pm$ 0.6   | 329.6 $\pm$ 12.8 |
| Marl (Lefkosia center)                                      | 7.1 $\pm$ 0.3                                                 | 8.9 $\pm$ 0.3    | 187.3 $\pm$ 7.3  |
| Marl (Lefkosia suburbs)                                     | 30.8 $\pm$ 0.9                                                | 41.2 $\pm$ 1.2   | 433.6 $\pm$ 16.7 |
| Melange                                                     | 52.8 $\pm$ 1.5                                                | 16.0 $\pm$ 0.5   | 392.5 $\pm$ 15.0 |
| Montmorillonite (Bentonitic clay)                           | 40.7 $\pm$ 1.1                                                | 18.3 $\pm$ 0.6   | 278.9 $\pm$ 10.8 |
| Paphos beach deposits                                       | 4.8 $\pm$ 0.2                                                 | 6.3 $\pm$ 1.2    | 147.3 $\pm$ 1.6  |
| Pediaios river alluvium                                     | 13.4 $\pm$ 0.2                                                | 17.6 $\pm$ 1.4   | 261.3 $\pm$ 1.5  |
| Red clay soil (terra rossa)                                 | 38.3 $\pm$ 0.5                                                | 21.0 $\pm$ 0.5   | 438.5 $\pm$ 10.1 |
| Stratified mamonia                                          | 20.0 $\pm$ 0.6                                                | 7.9 $\pm$ 0.3    | 245.3 $\pm$ 9.5  |

**Table 3.** Indoor radon concentrations by geological rocks types (adapted from [73]).

| Geological Classes                  | No. of Sites (%) | Mean (Bq·m <sup>−3</sup> ) |
|-------------------------------------|------------------|----------------------------|
| Acid rocks                          | 183 (5%)         | 192                        |
| Alluvial fan                        | 136 (4%)         | 125                        |
| Alluvial plain                      | 833 (24%)        | 66                         |
| Alluvial plain from mountain valley | 213 (6%)         | 168                        |
| Basic rocks                         | 32 (1%)          | 83                         |
| Debris                              | 246 (7%)         | 207                        |
| Dolomite rocks                      | 246 (7%)         | 198                        |
| Foothill deposit                    | 667 (19%)        | 118                        |
| Limestone                           | 333 (10%)        | 137                        |
| Metamorphic rocks                   | 174 (5%)         | 148                        |
| Moraine                             | 437 (12%)        | 92                         |

As can be seen in Table 3, Borgoni et al. (2011) delineated a correlation between varying geological rock types and indoor radon concentrations across different sites [73]. The investigation incorporated 3467 sites, with each site falling under one of the eleven geological categories. The highest mean radon concentration ( $207 \text{ Bq}\cdot\text{m}^{-3}$ ) was observed in locations characterized by debris formations, followed by dolomite rocks and acid rocks, presenting mean concentrations of  $198 \text{ Bq}\cdot\text{m}^{-3}$  and  $192 \text{ Bq}\cdot\text{m}^{-3}$ , respectively. The lowest mean concentration was detected in basic rock areas ( $83 \text{ Bq}\cdot\text{m}^{-3}$ ), while sites on the alluvial plain had a mean of  $66 \text{ Bq}\cdot\text{m}^{-3}$ , despite constituting the largest share of the sample size at 24%. Although sites on moraine formations accounted for a significant 12% of the sites, they exhibited a moderate mean concentration ( $92 \text{ Bq}\cdot\text{m}^{-3}$ ). These findings reveal the direct influence of geological classes on indoor radon levels, underscoring the importance of considering local geology in risk assessments for radon exposure. The results raise additional questions about the mechanisms leading to the observed variability and stress the need for further investigations to develop comprehensive radon mitigation strategies.

Aghdam et al. (2021) investigated the epidemiological implications of radon and thoron exposure in Ireland, delineating the geographical distribution of these elements, their decay products, and their correlation with lung cancer incidence [74]. The study identifies a particular concern in County Carlow, which records the highest mean indoor radon level. They emphasize the scarcity of studies addressing dose coefficients for thoron and its decay products, despite findings indicating potential thoron release in certain areas. The persistence of thoron decay products in indoor air and their associated radiation exposure suggest that further research is needed. The paper emphasizes the necessity of including thoron and its decay products in the analysis of priority areas due to potential adverse health effects, especially in rural areas where housing lacks concrete foundations. The study highlights the complexity of the radon and thoron potential landscape, noting areas of high radon but low thoron potential. Aghdam et al. (2021) suggest further testing and monitoring to improve the accuracy of radon potentials. The research presents a comprehensive analysis of radon/thoron exhalation rates, natural radioactivity levels, and related risks across multiple geological formations and soil types in Ireland, underlining the geology's role as a controlling factor and the importance of thoron progeny measurements for effective dose estimates. The authors also propose using airborne estimated values as a promising tool for predicting radon/thoron potentials, offering a more nuanced, geologically-informed understanding of radiation exposure risks.

### 2.3.2. Ventilation and Air Pressure

Well-ventilated constructions tend to have lower concentrations of radon, as the gas is diluted and dispersed into the outside air [75]. However, in buildings with insufficient ventilation, radon can accumulate, resulting in higher concentrations [76]. Additionally, differences in pressure between the interior and exterior of a building can create a suction effect, attracting radon into the building [77]. In poorly ventilated spaces, the buildup of radon gas can pose a significant risk to human health, particularly in areas with high levels of radon [78]. To mitigate this risk, it is important to ensure that buildings are properly ventilated, especially in areas with high levels of radon in the surrounding soil and rock. Ventilation systems, such as air exchange systems, can be installed to maintain a healthy indoor environment and reduce the risk of exposure to radon [79]. The study by Schubert et al. (2018) represents an important investigation into the concentrations of radon in indoor environments, which are a potential health hazard to the inhabitants of these spaces [80]. The study focused its discussion on the diverse factors influencing daily and multi-day variations in radon concentration. There are differing views on the relative importance of these variables, which include (i) the periodic forced ventilation of homes; (ii) the temporal variation of radon exhalation from soil and building materials caused, for example, by varying moisture content; and (iii) daily and multi-day temperature and pressure patterns. Forced ventilation and unspecified radon emissions are successfully excluded from the discussion of the effects of temporal climatic conditions in this study.

The findings show that the indoor/outdoor pressure gradient is the primary factor in any interior space's ongoing air renovation, which affects radon concentration in both daily and multi-day patterns. The day/night cycle of the indoor temperature, which is connected to an expansion or contraction of the internal air volume, is the primary cause of the daily recurrent changes in the pressure gradient. On the other hand, multi-day patterns are mostly caused by intervals of negative interior air pressure, which are brought on by intervals of high wind speeds as a result of Bernoulli's principle.

Another study by Zafrir et al. (2020) underscored temperature as the principal factor responsible for the observed temporal patterns across multiple timescales, ranging from less than an hour to years [81]. The variability of radon and temperature was remarkably similar on a seasonal scale, with both peaking in the summer. Daily variations were closely tied to the temperature gradient between the interior and exterior of the test environment. The influences of temperature included temperature-driven air ventilation and temperature-driven radon migration through a function dependent on the thermal gradient within the porous medium.

### 2.3.3. Building Materials

Although the main source of radon in indoor spaces is the soil and underlying rocks, some building materials can also release small amounts of radon [82]. For example, concrete and certain types of bricks and stones can contain traces of uranium and radium, which can generate radon over time [83]. The extent to which building materials contribute to indoor radon levels depends on several factors, including the type of material, its age, and the level of radionuclides present [84]. While the contribution of building materials to indoor radon levels is generally minor compared with that of soil and rock, it is still important to consider when assessing the overall risk of radon exposure [85]. Building materials that contain high levels of radionuclides, such as granite or other natural stones, can be a significant source of radon if used in large quantities in a building [75]. A recent study presented by Frutos-Puerto et al. (2020) examined the exhalation and emanation of radon and thoron from a variety of building materials from the Iberian Peninsula [86]. The authors concluded that both gases can be released from building materials into indoor atmospheres. This research found correlations between the exhalation rates of these gases and their parent nuclide exhalation concentrations (radium/thorium). Notably, zircon exhibited the highest concentration values of  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  as well as the highest exhalation and emanation rates. Certain granites also demonstrated an annual effective dose that exceeded the  $1\text{ mSv}\cdot\text{y}^{-1}$  exposure limit recommended for the public by European regulations. In their study, Sahoo et al. (2007) carried out radiometric analyses on various building materials from the Gujarat region in India, drawing attention to the elevated concentrations of natural radionuclides, particularly in fly ash samples and silica fume [87]. These higher concentrations notably contributed to an increased gamma dose in such materials. Considering the local cement industry's use of silica fume in manufacturing, the researchers correlated these higher levels of radioactivity with elevated radionuclide content in cement products, especially white cement. However, the annual effective doses and radium equivalent values for these materials were within the recommended levels. Interestingly, Sahoo et al. observed no linear relation between the emanating factor or mass exhalation rate and the radium content in the analysed samples. This may be attributed to how radon, a decay product of radium, is released from crystal lattices through various mechanisms. The researchers found an approximate linear correlation between the mass exhalation rate and the emanation factor, possibly due to the standardization of the sample's physical properties through powdering and drying prior to analysis. The study concluded that precautions must be taken to mitigate radon emission in dwellings constructed with fly ash bricks. Furthermore, Sahoo et al. advocated the adoption of their method to estimate the emanation factor, providing an index to select building materials regarding potential radon levels in dwellings. The researchers argue that although in situ values are ideal, they are difficult to obtain, hence the necessity of their method and the importance of considering factors such as radon

content, bulk density, porosity, moisture content, and air exchange rate when predicting indoor radon levels. In Table 4 are summarized the results obtained by Sahoo et al. (2007).

**Table 4.** Emanation factors for building materials and soil samples (adapted from [87]).

| Material         | No. of Samples | $^{226}\text{Ra}$<br>( $\text{Bq}\cdot\text{kg}^{-1}$ ) | $^{222}\text{Rn}$ Mass Exhalation Rate<br>( $\text{mBq}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ ) | $^{222}\text{Rn}$ Emanation Factor<br>(%) |
|------------------|----------------|---------------------------------------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------|
| Black sand       | 6              | $13 \pm 5$                                              | $18.8 \pm 6.4$                                                                                  | $20.4 \pm 8.2$                            |
| Cement (PPC)     | 5              | $29 \pm 4$                                              | $2.3 \pm 1.6$                                                                                   | $1.0 \pm 0.7$                             |
| Cement (SRC)     | 4              | $23 \pm 6$                                              | $2.2 \pm 1.9$                                                                                   | $1.4 \pm 0.8$                             |
| Concrete         | 6              | $21 \pm 5$                                              | $8.5 \pm 3.6$                                                                                   | $5.4 \pm 1.9$                             |
| Fired clay brick | 7              | $16 \pm 5$                                              | $6.1 \pm 3.4$                                                                                   | $7.8 \pm 3.4$                             |
| Flyash brick     | 6              | $81 \pm 11$                                             | $72.8 \pm 15.3$                                                                                 | $11.3 \pm 4.6$                            |
| Glazed tile      | 5              | $68 \pm 13$                                             | $0.8 \pm 0.7$                                                                                   | $0.2 \pm 0.2$                             |
| Lime             | 5              | $9 \pm 2$                                               | $14.6 \pm 4.9$                                                                                  | $20.8 \pm 5.2$                            |
| Marble           | 5              | $12 \pm 3$                                              | $1.1 \pm 1.0$                                                                                   | $1.2 \pm 1.1$                             |
| Silica fume      | 5              | $33 \pm 8$                                              | $12.5 \pm 4.4$                                                                                  | $5.0 \pm 1.7$                             |
| Soil             | 8              | $16 \pm 7$                                              | $23.5 \pm 11.8$                                                                                 | $19.2 \pm 6.1$                            |
| Vitrified tile   | 5              | $33 \pm 5$                                              | $0.3 \pm 0.3$                                                                                   | $0.1 \pm 0.1$                             |
| White cement     | 4              | $38 \pm 7$                                              | $12.3 \pm 5.6$                                                                                  | $4.3 \pm 1.8$                             |
| Yellow sand      | 6              | $10 \pm 4$                                              | $6.5 \pm 4.3$                                                                                   | $8.4 \pm 4.7$                             |

In these results, some of the materials, fired clay brick for instance, showed relatively low values for all three metrics, with a  $^{226}\text{Ra}$  concentration of  $16 \pm 5 \text{ Bq}\cdot\text{kg}^{-1}$ , an exhalation rate of  $6.1 \pm 3.4 \text{ mBq}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ , and an emanation factor of  $7.8 \pm 3.4\%$ . Conversely, fly ash brick exhibited significantly higher radioactivity levels, with an  $81 \pm 11 \text{ Bq}\cdot\text{kg}^{-1}$   $^{226}\text{Ra}$  concentration, a  $72.8 \pm 15.3 \text{ mBq}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$  exhalation rate, and an  $11.3 \pm 4.6\%$  emanation factor. The differences observed across materials suggest variable radon exposure risks depending on the specific material used. Interestingly, while certain materials such as vitrified and glazed tiles showed higher  $^{226}\text{Ra}$  activity concentrations, their  $^{222}\text{Rn}$  exhalation rates and emanation factors were quite low, indicating less radon released into the environment. In comparison, black sand and lime had high  $^{222}\text{Rn}$  exhalation rates and emanation factors despite lower  $^{226}\text{Ra}$  concentrations, and hence, potentially pose a higher radon risk. These findings underscore the importance of considering all three metrics when evaluating radon exposure risk from building materials and soils.

#### 2.3.4. Groundwater and Water Supply Systems

Radon can also be released into groundwater and water supply systems, especially where high uranium concentrations in the soil occur [88]. When water contaminated with radon is used for cooking, drinking, or bathing, the gas can be released into the air, contributing to the accumulation of radon indoors [88]. This presents a risk to individuals who may be exposed to high levels of radon through their water supply [89]. To mitigate this risk, it is important to regularly test water sources for radon and implement appropriate treatment measures if necessary, such as aeration or activated carbon filtration [90]. Additionally, individuals can take steps to reduce their exposure to radon in their water supply by using ventilation systems or installing point-of-use treatment devices [91]. Public health officials and water treatment facilities should also be aware of the potential risks associated with radon in water supplies and take appropriate measures to mitigate these risks to ensure the safety of the public [92]. For example, the study by Martins et al. (2013) focused on the relationship between the geological composition of the Amarante region in northern Portugal and radon concentrations in residential dwellings [93]. The geology of the region comprises Hercynian tardi-tectonics granites and Paleozoic metasediments. The study found that uranium, which is primarily contained within heavy accessory minerals such as apatite, zircon, monazite, uraninite, thorite, and thorianite in the rock, is a significant determinant of radon concentration. The most considerable uranium concentrations were found in the granites of Padronelo and of Telões, which contained 18.2 ppm and 10.3 ppm

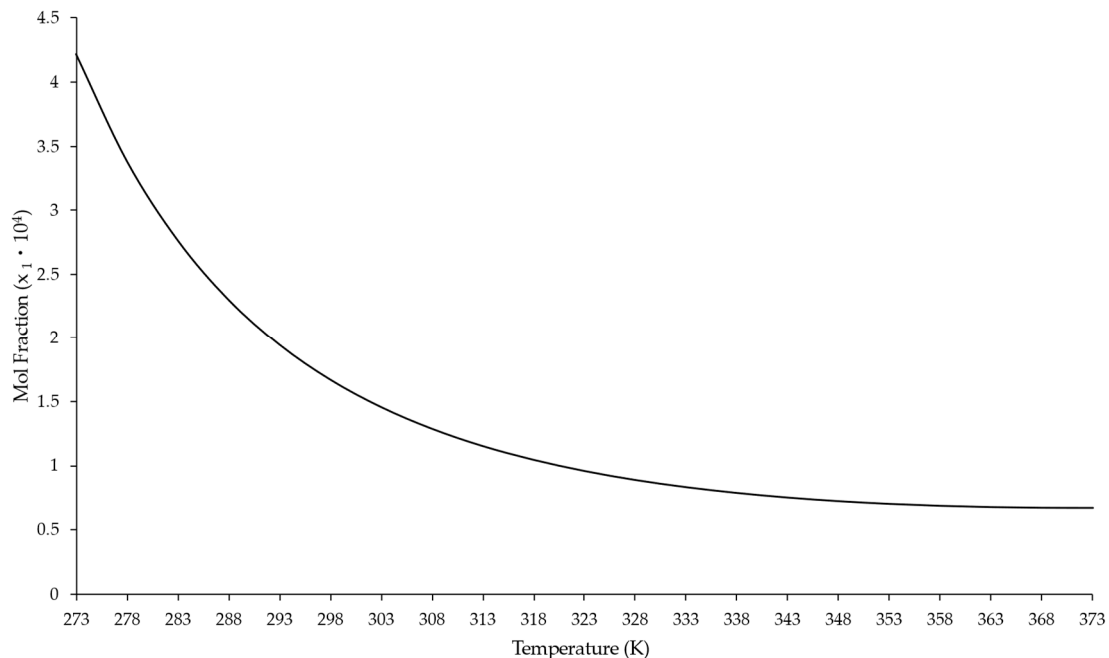
respectively. As a result, these granites had geometric means of 430 and 220 Bq·m<sup>-3</sup>, respectively, which were the highest radon concentrations. Metasediments, on the other hand, had geometric mean radon concentrations of 85 Bq·m<sup>-3</sup> and substantially lower uranium levels (1.6 ppm). It is interesting that the study discovered radiometric anomalies connected to localised fault systems that are impacting granitic rocks. These anomalies, where uranium concentrations can be quadruple usual background levels, showed uranium mobility and were probably the result of major mineral supports such as uraninite being dissolved in water. This finding implies a higher radon risk in places with these particular geological characteristics. The results of groundwater radionuclide concentrations were varied, with granitic lithologies showing the greatest activity. Metasediments, on the other hand, showed much lower values, which is consistent with the trends in soil uranium and radon concentrations. The absorbed dosage was discovered to be inversely linked to the uranium concentration of the rocks when it was measured with gamma spectrometers in close proximity to the rocks. This association shows that radon danger might be quickly estimated from the absorbed dosage.

In their study, Martins et al. (2019) investigated the variances between mineral and non-mineral water profiles through an analysis of hydrological and physicochemical properties, as well as radon concentrations [94]. This comprehensive study discovered distinctive features in two clusters of mineral water (C3 and C4), where high radon concentration and electric conductivity were found. In contrast, non-mineral water clusters (C1 and C2) had higher variation in altitude and precipitation. The results for the high-altitude collection points for the non-mineral water imply the importance of recharge in aquifer storage in cluster C2. The mineral clusters showed high physicochemical, radiological, and climatic attributes, further underlining the contrast with C1 and C2. They also found substantial differences in radon concentration within mineral water clusters. C3, for instance, demonstrated markedly low radon levels. This was attributed to a sampling issue caused by a closed circulation system, which led to the radon dissipating due to its short half-life. Moreover, their study illustrated the influence of multiple variables on radon production potential and contamination in groundwater using the PLS-PM model. Variables such as mineralogy texture, K<sub>2</sub>O content, Th content, and uranium content all played significant roles. This research contributed valuable insights for our understanding of how diverse factors influence the composition and safety of water sources, particularly the radon concentrations within them. Future work, as suggested by the authors, should integrate innovative modeling techniques to predict the flow and transport of radioactive contaminants.

### 2.3.5. Radon Solubility in Water

When radon is present in soil or rock, it can diffuse into groundwater where it is retained due to its solubility. This dissolved radon can then be released into the atmosphere when the water is agitated, for example, during household activities such as showering or washing dishes. The solubility of radon in water is influenced by factors such as temperature and salinity. As a general rule, radon is more soluble in cooler and less saline waters. It is important to note that the ingestion of water containing dissolved radon poses a lesser health risk compared with inhalation of radon gas. The study by Jobbágy et al. (2017) focuses on various technical aspects related to the measurement of radon in water [95]. This work refers to international standards dedicated to these measurements, such as ISO 13164-3:2013, ISO 13164-4:2015, and ASTM D5072-09. One of the key findings of this study is that a significant radon loss (2–5%) was observed from polypropylene containers within just one day after sampling, while radon leakage was negligible from other types of containers. Additionally, the study highlights that the concentration of radon in spring and hand pump water is influenced by the concentration of <sup>226</sup>Ra in rocks and the abundance of <sup>238</sup>U minerals. Despite the relatively low solubility of radon in water, its activity level in groundwater can be high due to the high level of radon content. The study also reports that depleted levels of thorium and uranium, elements notorious for their relationship with

radon, have been found. Yet perhaps the first, and therefore, very relevant approach to the subject is the analysis presented in the evaluation conducted by Rubin Battino, from the Department of Chemistry of the Wright State University (Dayton, OH, USA), in 1978 [96], which is schematized in Figure 1.



**Figure 1.** Radon solubility in water at a partial pressure of 101.325 kPa (adapted from [96]).

The analysis provides a clear view of the relationship between temperature and the molar fraction of radon. The molar fraction of radon is a measure of its solubility, and upon analyzing the data, a distinct trend is observed: whereas the temperature increases, the molar fraction—and thus the solubility of radon—decreases. At the beginning of the line, at a temperature of 273.15 K, the molar fraction of radon is 4.217. This value consistently decreases as the temperature rises. At 373.15 K, the molar fraction of radon is only 0.672, significantly lower than the initial value. This negative trend indicates that radon is less soluble in water at higher temperatures. The decrease in radon solubility with increasing temperature may be due to the fact that, with increasing thermal energy, radon molecules have more energy to escape from the solution and enter the gas phase. This pattern is quite common for gases in solution and suggests that, under warmer conditions, it can be expected that there is less radon dissolved in water and more present in the gas phase.

#### 2.3.6. Rn Accumulation

Indoor Rn accumulation is a topic of extensive research due to its significant implications for public health. Numerous studies, including those of Chen (2023) and Cigna (2005), have begun analyzing this phenomenon specifically in caves and mines, providing valuable insights into radon behaviour in these underground environments [97,98]. They shed light on average radon concentrations, variations, and factors influencing these variations.

Chen (2023) conducted a comprehensive review of radon exposure in non-uranium mines globally, analyzing the reported radon measurements in a total of 474 underground non-uranium mines. The paper also provides an estimation of potential radon exposure in Canadian mines, an area where data have been lacking. The average radon concentration across these mines was calculated as  $570 \text{ Bq}\cdot\text{m}^{-3}$ , though individual mine concentrations could vary greatly, from below the detection limit to above  $10,000 \text{ Bq}\cdot\text{m}^{-3}$ . This wide range indicates the variability in radon levels in different mining environments and underlines the importance of individual evaluations. The research also calculated the average equilibrium

factor between radon and its short-lived progeny, which is known as the F-factor, to be 0.34, with the potential to vary from 0.02 to 0.9 depending on the mine operation conditions. This factor is crucial in understanding the potential radiation exposure from radon decay products, which pose a more significant health risk than radon gas itself. Chen's analysis extends to assessing the annual effective radon dose to workers in Canadian non-uranium mines. For those working underground, the estimated annual effective radon dose was 3.76 mSv, with a possible range from 0.22 to 10 mSv, depending on factors such as ventilation and other operational conditions. Given that most mines in Canada are surface mines where outdoor radon concentration is low, the average occupational exposure to radon for the entire mining workforce—including underground workers, surface workers, and indoor workers—is estimated to be 0.9 mSv. Chen's work underlines the significance of radon exposure for workers in non-uranium mines, pointing out that these levels could potentially reach or even exceed Canadian thresholds for mandatory radiation monitoring and reporting. The research also emphasizes the necessity for further investigation into radon levels in Canadian underground non-uranium mines. Table 5 compiles the results of various previous studies, as reviewed by Chen (2023). This detailed table allows for a deeper understanding of the global variability in radon levels in non-uranium mines, further emphasizing the importance of Chen's conclusions.

**Table 5.** Results of radon measurements in underground coal mines, as presented by Chen et al. (2023), based on their review of results reported by previous works by Fan et al. (2016), Rao et al. (2001), Ghiassi-Nejad et al. (2002), Fathabadi et al. (2006), Qureshi et al. (2000), Mahmood and Tufail (2011), Skubacz and Michalik (2002), Bonczyk et al. (2022), Skubacz et al. (2016), Skubacz et al. (2019), Wysocka et al. (2021), Emirhan and Ozben (2009), Çile et al. (2010), Fisne et al. (2005) and Baldik et al. (2006) [99–120].

| Country   | Rn in Air ( $\text{Bq}\cdot\text{m}^{-3}$ ) | Reference                    |
|-----------|---------------------------------------------|------------------------------|
| Australia | $141 \pm 76$                                | Ralph et al. (2020)          |
| Brazil    | $227 \pm 59$                                | Salim and Bonotto (2019)     |
|           | $600 \pm 787$                               | Ayres de Silva et al. (2018) |
| China     | $80 \pm 106$                                | Shang et al. (2015, 2008)    |
|           | 530                                         | Chen et al. (2006)           |
|           | 400                                         | Chen et al. (2008)           |
|           | 169                                         | Fan et al. (2016)            |
| India     | $230 \pm 66$                                | Rao et al. (2001)            |
| Iran      | $321 \pm 109$                               | Ghiassi-Nejad et al. (2002)  |
|           | 220                                         | Fathabadi et al. (2006)      |
| Pakistan  | 192                                         | Qureshi et al. (2000)        |
|           | $89 \pm 28$                                 | Mahmood and Tufail (2011)    |
| Poland    | 609                                         | Skubacz and Michalik (2002)  |
|           | 261                                         | Bonczyk et al. (2022)        |
|           | $148 \pm 111$                               | Skubacz et al. (2016)        |
|           | $82 \pm 6$                                  | Skubacz et al. (2019)        |
|           | $67 \pm 57$                                 | Wysocka et al. (2021)        |
| Turkey    | 20                                          | Emirhan and Ozben (2009)     |
|           | 239                                         | Çile et al. (2010)           |
|           | $679 \pm 242$                               | Fisne et al. (2005)          |
|           | 117                                         | Baldik et al. (2006)         |

As can be seen in Table 5, Rn concentrations vary significantly both within and across countries. China shows the greatest range, from as low as  $47 \text{ Bq}\cdot\text{m}^{-3}$  to as high as  $1244 \text{ Bq}\cdot\text{m}^{-3}$ . This wide range could be due to different measurement techniques, the geological characteristics of the mines, or differences in ventilation systems and practices. Australia and Brazil also show substantial variation. In Brazil, the measurements range from

$227 \pm 59 \text{ Bq}\cdot\text{m}^{-3}$  to  $600 \pm 787 \text{ Bq}\cdot\text{m}^{-3}$ , which is a significant difference, while Australia has a more consistent but higher mean level of  $141 \pm 76 \text{ Bq}\cdot\text{m}^{-3}$ . Radon levels in India, Iran, and Pakistan are somewhat comparable, averaging around  $200\text{--}300 \text{ Bq}\cdot\text{m}^{-3}$ . Poland's results show a decrease over time from  $609 \text{ Bq}\cdot\text{m}^{-3}$  in 2002 to  $67 \pm 57 \text{ Bq}\cdot\text{m}^{-3}$  in 2021, suggesting improvements in mitigation efforts or changes in mining practices. Turkey's measurements range from  $20 \text{ Bq}\cdot\text{m}^{-3}$  to  $679 \pm 242 \text{ Bq}\cdot\text{m}^{-3}$ , reflecting a significant variation, which is potentially due to differences in geological conditions or measurement methods. In general, these results underline the importance of continuous monitoring and control of radon levels in underground mines, considering the health risks associated with radon exposure. They also suggest that factors such as geological conditions, mining practices, and mitigation efforts can significantly influence radon levels in these environments.

On the other hand, a previous work presented by Cigna (2005) provides an extensive overview of radon's physical characteristics, sources, its transportation in rock, and behaviour in cave environments. The author meticulously discusses the tools utilized for measuring radon concentrations, both active and passive, emphasizing their respective pros and cons for use in caves. An interesting highlight is the regulatory landscape surrounding radon in various countries. These regulations, enacted for radiation protection purposes, are examined in depth, along with recommendations issued by international organizations and materials and methods for implementing these limits. Cigna underscores radon's peculiarity as a component of cave atmospheres, noting its potential for studying cave microclimates and other phenomena. However, he also mentions that obtaining reliable information can be challenging due to the multitude of factors influencing radon concentration. A noteworthy point Cigna makes is about radon's supposed use in earthquake prediction. Although a connection between sudden radon concentration changes and earthquakes has been confirmed, verification using radon can only be achieved post-earthquake due to multiple potential causes for such fluctuations. The author further emphasizes the growing importance of radiation protection for individuals working in caves or other underground environments and suggests that estimations of death attributable to radon exposure may be overestimated but refrains from elaborating on this controversial topic as it is beyond the scope of his work. The author instead underscores the need for compliance with local regulations for cave activities, stressing that modifications to cave atmospheres, such as ventilation, should not be used to achieve this compliance due to potential serious disruptions to the cave environment. The recommended approach is limiting the time spent by workers in caves.

Upon comparing this with the work of Chen et al. (2023), it is clear that both emphasize the importance of monitoring and controlling radon levels in underground environments. However, the two works diverge somewhat in their approach and context, with Cigna focusing on the cave environment, regulatory aspects, and specific populations (cavers, workers, tourists), while Chen et al. concentrate on radon levels in coal mines across different countries. Table 6 presents the compiled results from Cigna (2005).

As shown in Table 6, the equilibrium factors of Rn and its short-lived decay products, measured in various caves across different countries, can vary significantly. The equilibrium factor, often represented as  $F$ , is an important parameter to understanding the potential health risks associated with radon exposure, as it relates to the proportion of radon progeny available for inhalation relative to the radon gas present. The equilibrium factor values range from 0.19 to 1.94, indicating a considerable variation in radon-related conditions in different caves. Most values fall between 0.4 and 0.9, aligning with the previously mentioned range from Chen's research. Hungary's Gellért-hill System exhibits a notably high equilibrium factor of 0.94, suggesting a high proportion of radon progeny relative to radon gas. This could indicate a potentially higher risk of radon exposure for those entering the cave, given that radon progeny is primarily responsible for delivering the radiation dose to humans. On the other end of the spectrum, the Jewel Cave in the USA shows a relatively low equilibrium factor of 0.19. This suggests that the proportion of short-lived radon progeny available for inhalation is lower, potentially implying a lower risk of

radiation exposure. An outlier in this data set is the Balcarka Cave in the Czech Republic, with an equilibrium factor of 1.94, which significantly exceeds the usual range of 0 to 1. This might be due to specific conditions in this cave or a possible error in measurement or data transcription. It is important to note that while the equilibrium factor provides valuable information about potential radon exposure, the actual risk is also influenced by factors such as the total concentration of radon, the duration of exposure, and the ventilation conditions within each cave. As such, these equilibrium factor values should be considered alongside these additional parameters for a comprehensive understanding of radon-related risks, and the data underscores the importance of site-specific assessments in understanding radon exposure risks. It also highlights the potential health risks posed by radon and its progeny in enclosed spaces such as caves, underlining the importance of continuous monitoring and research in these environments.

**Table 6.** Some values of the equilibrium factor measured in caves and presented by Cigna (2005), using as references the previous works by Virág et al. (1971), Yarborough et al. (1978), Ahlstrom and Fry (1978), Seymore et al. (1980), Burian and Stelcl (1990), Trotti et al. (1993), Szerbin (1996), Csizs et al. (2001) and Kávási et al. (2003) [97,121–129].

| Country        | Cave                    | Equilibrium Factor |
|----------------|-------------------------|--------------------|
| Hungary        | Gellért-hill System     | 0.94               |
|                | Szemlő Hill Cave        | 0.50               |
|                | Pál Valley Cave         | 0.48               |
|                | Therapeutic Cave        | 0.51               |
|                | Vass Imre Cave          | 0.53               |
| USA            | Carlsbad Caverns        | 0.44               |
|                | Crystal Cave            | 0.90               |
|                | Jewel Cave              | 0.19               |
|                | Lehman Cave             | 0.81               |
|                | Oregon Cave             | 0.66               |
|                | Round Spring Cave       | 0.98               |
|                | Wind Cave               | 0.46               |
|                | Howe Caverns            | 0.67               |
| Italy          | Grotta Grande Vento     | 0.69               |
|                | Grotta di Quinzano      | 0.55               |
| Czech Republic | Katerinska Cave         | 0.75               |
|                | Punkvevni Caves         | 0.86               |
|                | Sloupsko-sosuvské Caves | 0.87               |
|                | Balcarka Cave           | 1.94               |
| Japan          | Akiyoshi-do Cave        | 0.70               |
|                | Taisyō-do Cave          | 0.71               |
|                | Kagejiyō-do Cave        | 0.52               |
| Slovenia       | Postojna Cave           | 0.56               |

The subject of radon concentration in caves, and its implications for human health and environmental science, has also been the focal point of multiple studies conducted in Spain. Spanning almost two decades, these studies present an insightful progression in the understanding of radon behaviour and collectively highlight the significant strides made in understanding radon dynamics in Spanish caves, the potential health risks, and the broader implications for various research fields. The research chronology reveals a progression from initial monitoring and dose calculations to more complex studies of seasonal variations, spatial differences, and the influence of environmental factors. The accumulated knowledge underscores the importance of continuous monitoring and targeted interventions to mitigate health risks, contributing to the discourse on the safe and sustainable use of these unique environments.

One of the earliest studies, by Lario et al. (2005), investigated the radon concentration in Altamira Cave over a complete annual cycle [130]. The research, which aimed to calculate the annual effective dose for guides and visitors, reported radon levels ranging from  $186 \text{ Bq}\cdot\text{m}^{-3}$  to  $7120 \text{ Bq}\cdot\text{m}^{-3}$ , with an annual average of  $3562 \text{ Bq}\cdot\text{m}^{-3}$ . Notably, the effective doses did not exceed international recommendations, highlighting the relative safety for tourists and cave guides. This study established the groundwork for subsequent research in this area, with its focus on continuous monitoring and dose calculations. Six years later, Dueñas et al. (2011) conducted a similar annual cycle of radon concentration measurements in different halls of the Nerja Cave [131]. Unlike the previous study, this research aimed to detect seasonal variation patterns and relate them to various meteorological factors. This research expanded our understanding of the complexity of radon behaviour in caves, contributing to an emerging discourse on the implications of radon concentration variations for cave tourism. Fernandez-Cortes et al. (2013) carried out an insightful study in a shallow volcanic cave, using radon concentration to study hygrothermal variations [132]. This pioneering research established a link between radon activity and weather and microclimate conditions, which has substantial implications for diverse research fields, including volcanic and seismic activity monitoring, cultural heritage conservation, indoor air quality control, and the role of subterranean ecosystems as trace gas reservoirs. Two years later, Dumitru et al. (2015) expanded the geographic scope of the investigation to include several caves in Mallorca [133]. This study was significant for identifying caves where radon concentration exceeded the recommended action levels and posed health risks. It provided crucial insights into seasonal variability and spatial differences in radon concentrations. This study paved the way for more pragmatic applications of radon monitoring, providing crucial data for cave administrators and agencies regulating cave access. The study by Sainz et al. (2018) returned to Altamira Cave, utilising radon as an atmospheric tracer over a 30-year span [134]. This research demonstrated the utility of radon in revealing information about gaseous exchanges inside caves and with the external environment. The study noted how changes, such as the installation of a second closure, drastically reduced the connection between cave chambers, indicating the long-term impact of human intervention on cave environments. Most recently, Salazar-Carballo et al. (2022) examined the radon concentration dynamics in La Cueva del Viento, a volcanic lava tube in Tenerife Island [135]. The study found that rain and external air temperature significantly influenced the seasonal and daily variations in indoor radon concentrations. Importantly, this research determined the annual effective doses received by guides and visitors to be safe. However, it also recommended classifying La Cueva del Viento as a “Monitoring zone” requiring a regular monitoring program, pointing to the need for continuous monitoring and vigilance to ensure safety.

Of particular interest is the Castañar de Ibor cave in Spain, a subterranean karst system with distinct characteristics, which presents extraordinarily high levels of radon gas concentration. Fernandez-Cortes et al. (2009) provides a baseline understanding of the cave’s microclimate, noting its stability and sensitivity to environmental changes [136]. The study emphasizes the cave’s high and consistent radon content (average value of  $32,200 \text{ Bq}\cdot\text{m}^{-3}$ ) that varies in response to meteorological conditions, barometric fluxes, and anthropogenic influences such as uncontrolled cave entrance openings. A closer examination of the radon levels by Lario et al. (2006) revealed an annual average of  $32,246 \text{ Bq}\cdot\text{m}^{-3}$  with a peak reaching  $50,462 \text{ Bq}\cdot\text{m}^{-3}$  in April 2005 [137]. The research suggests that the radon concentration variations are primarily driven by differences in internal and external temperatures. To mitigate the associated radiation risks, time-limited visits and pre-visit ventilation measures were introduced, leading to a 10–12% reduction in radon levels during visits. Fernandez-Cortes et al. (2011) further elaborates on the interplay between cave and external conditions, highlighting two microclimatic patterns: trace gas storage in the cold-wet season and  $\text{CO}_2$  emissions during the warm-dry season [138]. The research underlines the role of climatic factors such as temperature differentials, cave air pressure, rainfall, and anthropogenic factors in influencing gas concentrations within the

cave. In the most recent study, Alvarez-Gallego et al. (2015) confirmed the high radon concentration, noting a seasonal pattern of summer minimums and fall maximums [139]. The study posits that reductions in air-filled porosity in soil and rock due to condensation or rainfall could be responsible for this seasonal trend. In terms of safety measures, the study proposes adjustments to touristic paths according to radon concentration distribution. Collectively, these studies contribute to a nuanced understanding of the Castañar de Ibor cave's microclimate and its high radon levels, pointing to the need for effective management strategies to balance tourism interests with health and safety concerns. These studies also contribute valuable information which complements the lists provided by Cigna (2005) and Chen et al. (2023).

### 3. Health Risks Associated with Radon Exposure

The World Health Organization (WHO) recognizes radon as a leading cause of lung cancer worldwide, and exposure to radon is a significant public health concern [140]. While there are several sources of radon exposure, indoor radon is the most concerning due to the potential for high concentrations in confined spaces [141]. It is estimated that up to 14% of lung cancer deaths worldwide are caused by radon exposure, highlighting the importance of addressing this issue for public health [142]. The WHO recommends that national authorities implement policies and programs to reduce exposure to radon in indoor environments, including testing and mitigation strategies [143]. Education and awareness campaigns are also important to increase public knowledge and promote action to reduce exposure [144]. Currently, the literature identifies the following potential impacts on human health resulting from exposure to radon:

- The relationship between radon exposure and lung cancer is well established [145]. When radon is inhaled, its radioactive particles can deposit in the lining of the lungs [146]. As radon and its radioactive descendants, such as  $^{218}\text{Po}$  and  $^{214}\text{Po}$ , decay, they emit radiation that can damage the DNA of lung cells and lead to the formation of tumours [147]. Epidemiological studies have shown that radon exposure is the second leading cause of lung cancer, after smoking [148]. Smokers exposed to radon have an even greater risk of developing lung cancer [140]. The study by Pershagen et al. (1994) provides a comprehensive analysis of the risk of lung cancer associated with residential radon exposure [149]. This study was conducted in Sweden and included 586 women and 774 men, aged between 35 and 74 years, who were diagnosed with lung cancer between 1980 and 1984. For comparison purposes, 1380 female controls and 1467 male controls were studied. The levels of radon measured in the residences of the study participants followed a log-normal distribution, with geometric and arithmetic means of 1.6 and 2.9 pCi/L, respectively. The results showed that the risk of lung cancer increased in relation to both estimated cumulative and time-weighted radon exposure. Compared with time-weighted average radon concentrations of up to 1.4 pCi/L, the relative risk was 1.3 (95 percent confidence interval, 1.1 to 1.6) for average radon concentrations of 3.8 to 10.8 pCi/L, and it increased to 1.8 (95 percent confidence interval, 1.1 to 2.9) at concentrations exceeding 10.8 pCi/L. An important aspect of this study was the interaction between radon exposure and smoking in relation to lung cancer. The interaction exceeded additivity and approached a multiplicative effect, suggesting that smoking may increase the risk of lung cancer associated with radon exposure. The study by Darby et al. (2005) was a collaborative analysis of individual data from 13 case-control studies on residential radon and lung cancer, encompassing nine European countries [150]. The sample included 7148 cases of lung cancer and 14,208 controls. The findings showed that the average measured radon concentration in the residences of the control group was  $97 \text{ Bq}\cdot\text{m}^{-3}$ , with 11% measuring over  $200 \text{ Bq}\cdot\text{m}^{-3}$  and 4% measuring over  $400 \text{ Bq}\cdot\text{m}^{-3}$ . For the lung cancer cases, the average concentration was  $104 \text{ Bq}\cdot\text{m}^{-3}$ . The research found a significant correlation between radon exposure and lung cancer risk. The risk of lung cancer increased by 8.4% (with a 95% confidence interval between 3.0% and 15.8%) for each

100 Bq·m<sup>-3</sup> increase in measured radon concentration. This corresponds to an increase of 16% (5% to 31%) per 100 Bq·m<sup>-3</sup> increase in usual radon, i.e., after correction for the dilution caused by random uncertainties in measuring radon concentrations. The dose–response relationship appeared to be linear, with no threshold, and remained significant in analyses limited to individuals from homes with measured radon less than 200 Bq·m<sup>-3</sup>. The proportional excess risk did not significantly differ with the study, age, sex, or smoking status. In the absence of other causes of death, the absolute risks of lung cancer by age 75 at usual radon concentrations of 0, 100, and 400 Bq·m<sup>-3</sup> would be about 0.4%, 0.5%, and 0.7%, respectively, for lifelong non-smokers, and about 25 times higher (10%, 12%, and 16%) for cigarette smokers.

- The health risks associated with radon exposure increase with cumulative exposure over time [151]. This means that even low or moderate levels of radon exposure over a long period can increase the risk of lung cancer [152]. This is especially important for individuals who spend a significant amount of time indoors, such as those who work from home or the elderly [153]. Mitigation strategies, such as improving ventilation, sealing cracks and gaps in foundations, and installing radon reduction systems, can significantly reduce radon levels in indoor environments [154]. It is also important to note that individuals who smoke are at an even greater risk of developing lung cancer from radon exposure, and therefore, should take extra precautions to reduce exposure [140]. A study by Tomasek et al. (2008) focused on examining the relationship between radon exposure and lung cancer risk in uranium miners from France and the Czech Republic [151]. They studied a group of 10,100 miners who had long-term, low-level exposure with a mean exposure time of 10 years, averaging fewer than 60 working-level months (WLM). With a total of 574 lung cancer fatalities recorded, 187% more than what would be predicted based on national statistics, the study concluded that the risk of lung cancer was much greater in this demographic. Cumulative radon exposure was closely linked to the elevated risk. According to the observed exposures, the estimated total extra relative risk per WLM was determined to be 0.027 (95% CI: 0.017–0.043). The authors discovered that for people who were exposed at the age of 30 and with 20 years since exposure, the extra relative risk per WLM was 0.042. For each ten-year rise in age at exposure and time since exposure, this risk fell by almost 50%. The study discovered no inverse exposure rate impact below 4 WL in terms of exposure rates. The outcomes were in line with the BEIR VI report's estimations based on the concentration model when the exposure rate was less than 0.5 WL. The researchers emphasised that an important element with a substantial impact on their findings was the accuracy of exposure estimations. The most significant impact modifiers were shown to be age at exposure and time since exposure. These findings offer important insights for creating efficient methods to control and lower radon-related health hazards since they imply that both the time and duration of radon exposure are key factors in lung cancer risk in uranium miners.
- Children are considered a vulnerable group regarding radon exposure as they have a higher respiratory rate than adults and their lungs are still developing [155]. This means that in a given amount of inhaled air, children may absorb a higher amount of radon than an adult [156]. Additionally, children spend more time at home than adults, especially at younger ages when they attend school less frequently and spend most of their time at home. These factors increase the potential for exposure to radon in indoor environments, showing therefore, the importance of implementing mitigation measures in homes and schools to reduce the risk of exposure for children [157]. The study by Hill et al. (2005) provides valuable insights into the perception of radon exposure risk among rural residents receiving public health services [158]. The study based on a cross-sectional methodology and including 31 rural families showed a serious lack of knowledge about the dangers of radon exposure. It was discovered that 32% of people were exposed to high airborne radon levels (defined as 4 pCi/l). However, 39% of participants disagreed that their children's long-term health would improve

if they were exposed to less radon, 52% were unsure, and more than a third of individuals overestimated the seriousness of the health impacts that radon exposure may have. Only 21% of participants accurately identified their risk level after correcting for chance. These findings point to a worrying discrepancy between the real danger of radon exposure and how rural communities perceive that risk. This shows that there is a need for increased radon risk education and awareness, especially in rural regions where exposure can be higher. The authors came to the conclusion that low-income rural residents are unaware of the danger of radon exposure or the harmful effects of exposure. This emphasises the significance of public health initiatives meant to raise radon awareness and encourage rural residents to test themselves voluntarily. Making decisions on radon testing and mitigation requires having a thorough awareness of the danger of radon exposure. Several studies have suggested that exposure to radon may be associated with other types of cancer, such as leukaemia and stomach cancer, in addition to lung cancer [159–161]. However, these associations are less clear and require further research to be confirmed. On the other hand, workers in mines, underground jobs, and construction industries may be exposed to higher levels of radon compared with the general population [151]. It is now recognized that the implementation of appropriate measures to monitor and reduce the exposure to radon in the workplace is of high relevance to reducing risk and improving public health. Further research is, however, necessary to better understand the relationship between radon exposure and different types of cancer, and to inform policies and practices aimed at reducing the risk of exposure to radon in various settings. The study by Kohli et al. (2000) conducted in Sweden aimed to evaluate the relationship between exposure to ground radon and leukaemia among children, utilising existing population and disease registers [162]. The study, which examined all infants born in the county of Stergötland between 1979 and 1992, was planned as an ecological correlation study. The approach involved cross-referencing addresses in the population and property records to map each child to the centroid coordinates of the property they resided in. Radon maps were superimposed over population maps, and levels of exposure to radon were classified as high, normal, low, or unknown. The 53,146 children who participated in the research were found to have 90 malignancies, according to the study's findings. The standardised mortality ratios (SMRs) for children born in high-, normal-, and low-risk locations for acute lymphoblastic leukaemia (ALL) were 1.43, 1.17, and 0.25, respectively. In comparison with the low-risk group, the relative risk for the high-risk and normal-risk groups was 4.64 and 5.67, respectively. The connection between ALL and continuous residency in low- or high-risk locations showed a similar pattern. Radon risk levels, however, were not linked to any other malignancies. The study concluded that children who are born and raised in regions with low ground radon risk are less likely to develop ALL than children who are born and raised in places with normal or high risk. This research adds to the growing body of information pointing to a possible link between radon exposure and the prevalence of ALL in children. Because of the limitations imposed by the study's ecological design, more research is required to confirm and comprehend this connection. Another study by Tong et al. (2012) represents a significant contribution to our understanding of the impact of radon exposure in domestic environments on the incidence of childhood leukaemia [163]. The relationship between radon exposure and other cancers, such as leukaemia, has not always been shown, despite evidence from animal and human epidemiological research that there is an elevated risk of lung cancer in the general population. Their review sought to clarify the relationship between home radon exposure and the prevalence of childhood leukaemia by synthesising the data from ecological and case-control studies conducted in populations exposed to radon, taking into account dose estimation and evidence of radon-induced genotoxicity. The analysis of 12 ecological studies revealed a positive correlation between heightened radon levels and a higher incidence of childhood leukaemia in 11 studies, with 8 of these

correlations being significant. Several case-control studies on indoor radon exposure and childhood leukaemia were reviewed alongside ecological research, and the majority of studies found a modest connection, with only a few demonstrating significance. The report also notes that the radon dose estimate is a significant source of ambiguity in radon risk assessment. One of the variables influencing risk estimations in case-control research is the techniques used to measure radon exposure in children's homes. Through the use of genetic endpoints such as chromosomal aberration, micronuclei formation, gene mutation, and deletions and insertions, the impacts of radon-induced genetic damage were examined both in vitro and in vivo. Applying a meta-analysis, it was shown that exposure to indoor radon increased the incidence of both acute lymphoblastic leukaemia (ALL) and generalised paediatric leukaemia.

Understanding the long-term health effects of radon exposure is very important, and extensive research in this area is necessary for assessing the potential risks associated with prolonged radon exposure and developing effective strategies for prevention and mitigation. Longitudinal studies and comprehensive analyses of large-scale datasets are essential for assessing the cumulative impact of radon exposure, while considering factors such as geology, climate, and seasonality. The findings from such research endeavors will empower policymakers, public health authorities, and individuals to implement proactive measures and create healthier indoor environments.

#### **4. Risk Assessment and Mitigation**

##### *4.1. Techniques Used to Measure Radon Concentration in Rocks and Soils*

###### **4.1.1. Solid State Nuclear Track Detectors (SSNTD)**

Solid state trace detectors, such as alpha track detectors, are a common and low-cost technique for measuring radon concentration [164]. These devices contain a sensitive material that records the damage caused by the alpha particles emitted by radon and its radioactive decay products [165]. After a period of exposure, the detector is analysed in the laboratory to determine the radon concentration. This technique is suitable for long-term measurements and provides an average of the radon concentration during the exposure period. The alpha track detectors are small and can be easily placed in various locations within indoor environments to obtain a representative sample of the radon concentration [166]. The detectors are sensitive enough to measure low levels of radon, making them a useful tool for assessing indoor air quality and identifying areas with elevated radon levels. Solid state trace detectors are widely used in radon measurement programs and are recommended by various international organizations as a reliable and cost-effective method for measuring radon concentration in indoor environments [167]. However, the accuracy of the measurements can be influenced by factors such as humidity, temperature, and air circulation, and periodic calibration of the detectors is necessary to ensure their reliability.

###### **4.1.2. Ionization Chambers**

Ionization chambers are devices that measure radon concentration by detecting ionized particles produced by the radioactive decay of radon and its decay products [168]. This technique is sensitive and can provide quick and accurate measurements of radon concentration. However, ionization chambers are typically more expensive and require periodic calibration and maintenance [169]. This technique is particularly useful for measuring radon concentration in indoor environments where the risk of exposure is higher [170]. Additionally, measurement is quick and can be performed in real-time, allowing for immediate results. These devices require periodic calibration and maintenance to ensure measurement accuracy, which may further increase the cost of using these techniques. Despite these limitations, ionization chambers are widely used worldwide for measuring radon concentration in indoor environments, especially in locations where the risk of exposure is higher, such as in homes and workplaces [152].

#### 4.1.3. Liquid Scintillation

The liquid scintillation technique for measuring radon involves extracting radon gas from soil or rock samples and dissolving it in a scintillating liquid [171]. When radon decays, the alpha particles emitted interact with the scintillating liquid, producing pulses of light that are detected and counted by a photomultiplier [172]. This technique is sensitive and can provide rapid results, but it can be more complex and expensive than other techniques. Liquid scintillation can be used in conjunction with other techniques, such as gamma-ray spectrometry, to provide a more comprehensive assessment of the radiation environment [173]. While the liquid scintillation technique is sensitive and accurate, it has some limitations. The technique requires specialized equipment and trained personnel, which can make it more expensive and time-consuming than other techniques [174]. This technique is not suitable for measuring radon in indoor air, as the extraction of radon gas from air samples is more complex and requires different equipment [15].

#### 4.1.4. Gamma Spectroscopy

Gamma spectroscopy is an indirect technique for measuring the concentration of radon in rocks and soils, and is based on the detection of gamma radiation emitted by the radioactive decay products of radon, such as lead-214 and bismuth-214 [175]. Gamma spectroscopy can be performed in situ or in the laboratory using collected samples. While this technique can provide useful information about the presence of uranium, thorium, and other radioactive elements, it does not directly measure the concentration of radon and may be less precise than other techniques [176]. However, gamma spectroscopy can be used as a complementary technique to measure radon indirectly by detecting the decay products of radon, which are also radioactive and emit gamma radiation [177]. This technique can be particularly useful in areas with complex geology, where the concentration of radon may vary widely depending on local geological factors [178].

#### 4.1.5. Soil Permeability Measurement and Modeling

Another approach to assessing the concentration of radon in soils and rocks is to measure the soil permeability (the ease with which radon can move through it) and the concentration of uranium and thorium in rocks and soils [179]. The concentration of uranium and thorium in rocks is a strong indicator of the amount of radon that can be generated since these radioactive elements decay and generate radon in their decay products [15]. Measuring soil permeability is a more indirect approach to assessing radon concentration since permeability affects the ease with which radon can move through the soil and reach indoor environments [179]. In areas with high permeability, radon can move more easily and reach greater distances, increasing the risk of exposure. On the other hand, in areas with low permeability, radon can become trapped in the soil and not reach indoor environments. Therefore, measuring soil permeability is important to identify high-risk areas and develop effective mitigation strategies. Combining soil permeability measurement with the concentration of uranium and thorium in rocks and soils can provide a more accurate assessment of radon concentration and the risk of exposure in a given area [180].

#### 4.1.6. Uranium and Thorium Concentration Measurement Methods in Soil

The measurement of uranium and thorium concentrations in soil is an essential task in the field of environmental radioactivity due to their long half-lives and potential health risks [181]. Various methods have been developed to perform this task, with gamma-ray spectrometry being one of the most widely used due to its non-destructive nature and ability to provide quick results. In this method, a high-purity germanium detector is commonly employed to measure the gamma radiation emitted by the decay of uranium and thorium isotopes present in the soil samples [182]. However, this method requires careful calibration and correction for self-absorption of gamma rays in the sample. For more precise measurements, particularly when lower concentrations are expected, more

sensitive methods such as alpha spectrometry or mass spectrometry may be used. Alpha spectrometry is often applied to measure the alpha particles emitted during the decay of uranium and thorium, while mass spectrometry can provide highly accurate measurements by determining the ratio of different isotopes [183]. However, both methods require more complex sample preparation procedures, including dissolution of the sample and separation of the elements of interest.

#### *4.2. Geographical and Seasonal Variations in Radon Concentration*

##### *4.2.1. Geographic Variations*

As previously stated, the concentration of radon in soil and air is strongly influenced by local geology. Areas with higher concentrations of uranium and thorium in rocks and soils tend to have higher concentrations of radon. For example, granite regions and areas with igneous and metamorphic rocks rich in uranium and thorium generally have higher concentrations of radon. In addition, the permeability of soil and rocks also influences the concentration of radon, with more permeable soils facilitating the movement of gas through the subsurface. Understanding these geological factors is important for identifying areas of high radon concentration and developing effective mitigation strategies. Gillmore et al. (2005) examined the application of seasonal correction factors to indoor radon concentrations in the UK, with a particular focus on the role of geology [34]. The intricacy of the UK's geological terrain, which is likely the most intricate in terms of both solid and surficial characteristics across short distances, was emphasised by the authors as a crucial reason for high indoor radon levels. The National Radiological Protection Board amassed a sizable database on which the study was based, which included information from small-scale surveys that started in 1976 and proceeded with a larger-scale survey in 1988. These studies have unequivocally demonstrated that indoor radon levels vary seasonally. However, the use of a seasonal adjustment factor may occasionally overstate or underestimate radon levels due to the wide range in the permeability of underlying materials and the complexity of the UK's geology. As a result, the authors propose using either seasonal adjustment factors with extreme caution or never using them at all. The case studies from the Northamptonshire area served as the basis for this study, which also included comparisons to other permeable geologies in the UK. The results raise concerns about the effectiveness of using seasonal correction factors uniformly across various geological landscapes and emphasise the necessity of taking local geological diversity into account when assessing indoor radon levels. In addition, Florică et al. (2020) conducted a comprehensive study to explore the various factors contributing to indoor radon accumulation, examining 100 case studies in Romania [184]. They confirmed that the geological characteristics of bedrock strongly influence radon emissions, yet noted that other factors, including permeability, building and architectural features, ventilation, and occupation patterns, also significantly determine radon's in-soil transport and indoor entry paths. The researchers found that the geological foundation could largely account for the majority of the radon values recorded in both soil and indoor air, thus emphasising the influence of geology on radon levels. The study also revealed intriguing correlations with housing characteristics. Older houses, particularly those built with earth-based materials, were found to be highly permeable to soil radon, potentially leading to higher indoor radon concentrations. Conversely, energy-efficient houses were found to have a higher predisposition to indoor radon accumulation, largely due to their design which often disregards the radon potential of the geological foundation. This oversight can lead to a decrease in the general indoor air quality. The findings from this study underscore the multifaceted nature of radon accumulation indoors and the need to consider a broad spectrum of natural and man-made factors in its assessment and mitigation.

##### *4.2.2. Seasonal Variations*

The concentration of radon can also vary seasonally due to changes in atmospheric conditions such as temperature, humidity, and barometric pressure [185,186]. In general,

radon concentrations tend to be higher during the winter months when the temperature difference between the inside and outside of buildings is greater. This temperature difference can create a suction effect, drawing radon into buildings. Additionally, ventilation is typically reduced in the winter, which can contribute to the accumulation of radon in indoor environments. On the other hand, during the summer months, increased ventilation and more uniform temperatures between the inside and outside of buildings can result in lower concentrations of radon. The study by Baltrėnas et al. (2020) investigated the variations in indoor radon concentrations as influenced by environmental factors, such as outdoor temperature, relative humidity, and air pressure, across different university building premises [185]. Every working day for eight months, measurements were taken in four different locations for the research. The study's findings indicated a significant relationship between indoor radon levels and outside temperatures as well as relative humidity. On the other hand, the connections between indoor radon levels and the air pressures inside and outside were the weakest. It is interesting to note that the relationship between radon levels and the surrounding environment changed depending on the location. A significant association between radon concentration and outside temperature was found, with values of 0.94 and 0.92, in two buildings where ventilation impact from inadvertent air leakage was prevalent throughout the winter. The association between radon levels and outdoor temperature, however, was shown to be negative in buildings with better airtightness ( $R = -0.96$  and  $R = -0.62$ ). The results point to high-quality air isolation in buildings as a potential contributor to higher indoor radon levels in the summer than in the winter. It emphasises how important seasonal fluctuations and hygrometric factors are to the behaviour of indoor radon concentrations.

#### 4.2.3. Daily Variations

The concentration of radon can also vary throughout the day due to daily fluctuations in temperature and atmospheric pressure, in addition to seasonal variations [185]. Although daily variations are generally smaller than seasonal variations, they can still be significant in some cases. The daily variations in radon concentration are influenced by various factors such as the rate of radon production, ventilation, and soil moisture. For example, during the day, the temperature and pressure typically rise, leading to increased soil gas flow and radon transport [187,188]. Conversely, at night, the temperature and pressure usually drop, resulting in less soil gas flow and reduced radon transport. The knowledge of these daily variations is important for understanding radon exposure patterns and designing effective mitigation strategies. In their 2009 study, Kolarž, Filipović, and Marinković explored the daily variations in indoor air ion and radon concentrations, highlighting their opposite effects on human health [189]. They found radon, a potentially lethal gas due to its association with lung cancer, to be a significant generator of air ions in the lower troposphere. The team measured air ion and radon concentrations in both outdoor and indoor environments, as well as their vertical gradients in residential buildings. Their study revealed a substantial correlation between positive air ion and radon concentrations indoors, with a correlation coefficient of approximately 0.7. Importantly, they observed that peak values for both outdoor and indoor concentrations occurred simultaneously, and a clear vertical gradient of concentrations was apparent in indoor measurements. The researchers concluded that the concentration of positive air ions could serve as an alternative method for assessing radon activity concentration, offering a valuable tool for monitoring this potentially hazardous gas.

#### 4.2.4. Influence of Climate and Topography

Other factors that can influence radon concentration in an area are climate and topography [190]. For instance, areas with higher precipitation can have wetter soils, which may reduce soil permeability and the mobility of radon [191]. In addition, topography can affect air circulation and radon dispersion, with areas in depressions or valleys having a higher potential for radon accumulation [192]. Temperature variations due to climate

and topography can also affect soil pressure, which can impact radon mobility. In their seminal work, Schumann and Gundersen (1996) explored the interplay between geologic, pedologic, and climatic factors in determining the radon emanation coefficient [193]. They discovered that a soil's radon emitting power and radon transport characteristics depend on a variety of variables, including its radium concentration, grain size, the position of radon parent atoms inside or on grain coatings, and the soil's moisture levels. It was interesting to see that soils from comparable parent rocks in different places had dramatically varying emanation coefficients, mostly as a result of the influence of climatic conditions on these soil properties. The authors also stressed the use of ground-based and aerial gamma radioactivity measurements as instruments for determining the power of radon sources. Gamma spectrometry measurements of the soil's radium content and soil gas or indoor radon concentrations were shown to be correlated regionally, indicating the impact of climatic and geologic conditions on intrinsic permeability and radon emanation coefficients. When paired with information on emanation coefficients, the gathered data on soil radium concentration, permeability, and moisture content were suggested as the foundation for creating quantitative prediction models for radon production in rocks and soils.

#### 4.3. Radon Risks Mitigation

##### 4.3.1. Assessment and Monitoring

Measuring radon concentration in indoor environments is an essential process to ensure the health and safety of the population [194]. Short-term radon detectors are typically used to provide an estimate of radon concentration over a period of a few days, while long-term radon detectors can provide a more accurate measure of radon concentration over a period of several months or even years [195]. Long-term measurement is particularly important in areas where radon concentration may vary significantly over the year due to factors such as seasonal variations and weather conditions [196].

##### 4.3.2. Ventilation

Increasing ventilation in indoor spaces is a simple and effective way to reduce radon concentrations [197]. This can be achieved by opening windows and doors, using mechanical ventilation systems such as exhaust fans and fans, or installing a heat recovery ventilation (HRV) system that exchanges indoor and outdoor air while maintaining the ambient temperature. Increasing ventilation helps to dilute the concentration of radon in the indoor air and reduce the overall exposure to the gas [198]. In addition to reducing radon levels, increasing ventilation can improve indoor air quality by reducing the concentration of other indoor air pollutants, such as carbon dioxide and volatile organic compounds (VOCs). However, it is important to note that increasing ventilation may not always be sufficient to bring radon concentrations below the recommended levels, and other mitigation measures may be necessary [199].

##### 4.3.3. Sealing Cracks and Openings

Sealing cracks and openings in floors and walls that are in contact with soil can effectively reduce the entry of radon into indoor spaces [200]. In addition to mastics, sealants, and membranes, other materials such as caulk and foam can also be used to seal openings. It is important to note that sealing alone may not eliminate radon entry, but it can significantly reduce its levels. In some cases, more advanced techniques such as soil suction or pressurization systems may also be necessary to further reduce radon levels [37]. It is important to consult with a qualified radon professional to determine the best course of action for each individual situation.

##### 4.3.4. Sub-Slab Radon Mitigation (SSD) System

Installing a sub-slab depressurization (SSD) system is an important strategy for reducing exposure to the radioactive gas in indoor environments [201]. This system works by creating negative pressure beneath the foundation slab, which prevents the entry of

radon into indoor spaces [202]. To accomplish this, pipes and fans are installed beneath the foundation slab to extract the radioactive gas from the soil and release it outside the building. In addition to reducing radon exposure, a sub-slab radon mitigation system can also have additional benefits, such as improving indoor air quality and reducing moisture in the soil, which can prevent health and structural problems [203]. However, installing this system can be a complex and expensive process, depending on the characteristics of the building and soil.

#### 4.3.5. Passive Soil Depressurization (PSD) Systems

Passive soil depressurization (PSD) is another strategy for reducing exposure to radon in indoor environments [204,205]. This system does not require fans and uses natural air convection to extract the radioactive gas from the soil. The PSD works by installing ventilation pipes in the soil below the foundation slab and connecting them to an exhaust system that releases the gas outside the building. Although less effective than an SSD system, PSD can be a low-cost and low-maintenance option in some situations. However, it is important to note that the effectiveness of PSD may be limited in areas with very wet or poorly permeable soils, or in locations with significant atmospheric pressure differences. In addition, PSD may not be suitable for buildings with high levels of radon, where the SSD system may be more appropriate.

#### 4.3.6. Construction and Design of Buildings

In the field of civil engineering, a very important aspect of the design and construction of new structures is the incorporation of measures to mitigate exposure to radon, which can pose significant health risks if it accumulates in indoor environments. It is paramount, therefore, to develop strategies to minimize its presence in the built environment. A myriad of preventative measures can be integrated into the design and construction process. One such measure involves the implementation of radon barriers. These barriers, typically composed of impermeable membranes, are an effective means of preventing radon infiltration from the soil into the building. Equally significant is the incorporation of robust ventilation systems in the building design. Proper ventilation can significantly reduce radon levels by encouraging air exchange, thus preventing the buildup of radon gas within the building. Site selection is another critical aspect to consider. Local geological conditions and soil radon concentrations can vary greatly, and understanding these can inform the decision-making process when identifying suitable construction sites. Choosing areas with lower radon concentration in the soil can limit the inherent potential for indoor radon accumulation. Modern buildings can be designed to include specific features, such as sub-slab depressurization systems. These systems can be installed during construction to create a pressure differential that prevents radon from entering indoor spaces, offering a further protective measure against this harmful gas. Therefore, it is imperative that civil engineers and architects consider the potential for radon exposure when designing and constructing new buildings. Through thoughtful design and construction, we can create built environments that are not only functional and aesthetically pleasing but also safe and healthy for their inhabitants.

### 5. Conclusions

This research probes the nexus between radon occurrence and geology, scrutinizing radon sources, its transport and accumulation mechanisms, alongside its implications for human health and mitigation tactics. Radon, a radioactive gas originating from the decay of uranium and thorium in soil and minerals, exhibits fluctuating concentrations contingent on geographic, diurnal, and seasonal factors such as geology, soil permeability, climatic conditions, and topography. The relationship between heightened indoor radon exposure and elevated lung cancer risk necessitates public health vigilance. Identifying areas with high radon concentration via regular indoor measurements is instrumental for devising effective mitigation strategies such as ventilation improvements, fissure sealing,

and exhaust system installation. Future research should aim for an improved comprehension of geographic and seasonal radon concentration variability and strive to create superior, cost-effective measurement and mitigation methods. Furthermore, studies must delve into the long-term health impacts of radon exposure to guide public health policies and practices. Public health initiatives ought to prioritize increasing radon exposure risk awareness, promoting regular indoor radon concentration monitoring, and fostering the adoption of effective mitigation tactics. Urban planning and building regulations should also integrate considerations of local geology and soil radon levels, thereby minimizing radon exposure through judicious site selection and building design.

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