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Review

Radon, Concrete, Buildings and Human Health—A Review Study

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Abstract: A comprehensive evaluation of the results obtained according to the measurement of radon gas in buildings and concrete, which is the most consumed material in the world after water, in accessible studies carried out in the last 40 years is the main objective of this study. The paper additionally aims to address the gap in the literature by comparatively determining which parameters affect radon–concrete and radon–building relationships. The scientific knowledge compiled within the scope of this article was presented under the main headings of radon and radon gas measurements in concrete and buildings. Radon gas, also known as the "invisible killer", is considered the second most important cause of lung cancer after smoking (the gas is responsible for 3–14% of lung cancer cases in the world). The results determined that radon concentration limits have been applied in the range of 100–400 Bqm^{-3} in houses and 100–3700 Bqm^{-3} in workplaces. Studies conducted on the exhalation rate of radon showed that the radon exhalation rate of concrete may be in the range of 0.23–510 Bqm^{-2} h^{-1}. The results of indoor radon concentration measurements revealed that values between 4.6 Bqm^{-3} and 583 Bqm^{-3} were obtained. Despite the existing literature, some researchers state that there is an urgent need for an improved and widely accepted protocol based on reliable measurement techniques to standardize measurements of the radon exhalation rate of construction materials and the indoor radon concentration of buildings.

Keywords: radon exhalation rate; indoor radon concentration; human health; concrete; building

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Citation: Bulut, H.A.; Şahin, R. Radon, Concrete, Buildings and Human Health—A Review Study. *Buildings* **2024**, *14*, 510. https://doi.org/10.3390/buildings14020510

Received: 12 December 2023
Revised: 30 January 2024
Accepted: 1 February 2024
Published: 13 February 2024

1. Introduction

Concrete, which has several superior features, such as the ease of its production process, its ability to provide the desired strength and durability values, architectural flexibility, and perfect compatibility with steel [1–4], is today the most frequently used [5–7] and most consumed (annual concrete production of 1 m^3 per person [8]) construction material. On the other hand, radioactive substances, entering the body through respiration and digestion and accumulating in the organs over time, can be found in food, air, and water [9,10]. Radon is a colorless, odorless, tasteless, chemically non-reactive radioactive gas that occurs spontaneously in nature [11,12]. Radon gas, which passes through existing voids and cracks and accumulates in buildings, can also enter indoor environments through water and some construction materials [13–16].

Radon gas, which accumulates in closed environments, has been determined a harmful gas that poses a danger to human health [17–21]. This gas can easily enter the body through respiration and accumulate in tissues, and when it exceeds a certain concentration value, it causes radiation-induced lung cancer [22–27]. There are many studies indicating radon gas as the second most frequent cause of lung cancer after smoking [28–30].

Many studies have been conducted on the concentration measurements of radon gas in concrete materials and reinforced concrete buildings in the last 40 years (e.g., [31–46]). Therefore, awareness has been raised on the subject. At the end of these studies, it is stated that among the components that constitute concrete, the cement and mineral additives obtained as industrial by-products play a major role in radon gas emissions [47–49]. Kovler [50] reported that fly ash has an increased concentration of Naturally Occurring Radioactive Materials (NORMs). Turhan et al. [51] stated that the industrial by-products such as slag, bauxite, fly ash, and phospho-gypsum obtained as a result of processing have a higher specific activity (radioactivity) than the raw materials and that these could be called technologically enhanced NORMs.

This article reviews the accessible studies on radon gas measurements on concrete and buildings undertaken over the last 40 years. The paper additionally aims to address the gap in the literature by comparatively determining which parameters affect radon–concrete and radon–building relationships. In this context, studies on the radon exhalation rate of concrete and the measurement of the indoor radon concentration in buildings were examined in detail. The article also includes information about the formation of radon gas, radon sources, and the effects of radon gas on human health.

2. Radon

The most important natural radiation source is radon, a radioactive gas [52,53]. It is approximately 7.5 times heavier than air. It can therefore easily affect plastic, leather, paper, paint, and construction materials [54,55]. Radon is produced from radium in the decay chain of uranium. The decay chain of Uranium-238, the most common form of uranium, including the formation of radon, is provided in Figure 1, and the basic characteristics of radon are provided in Table 1.

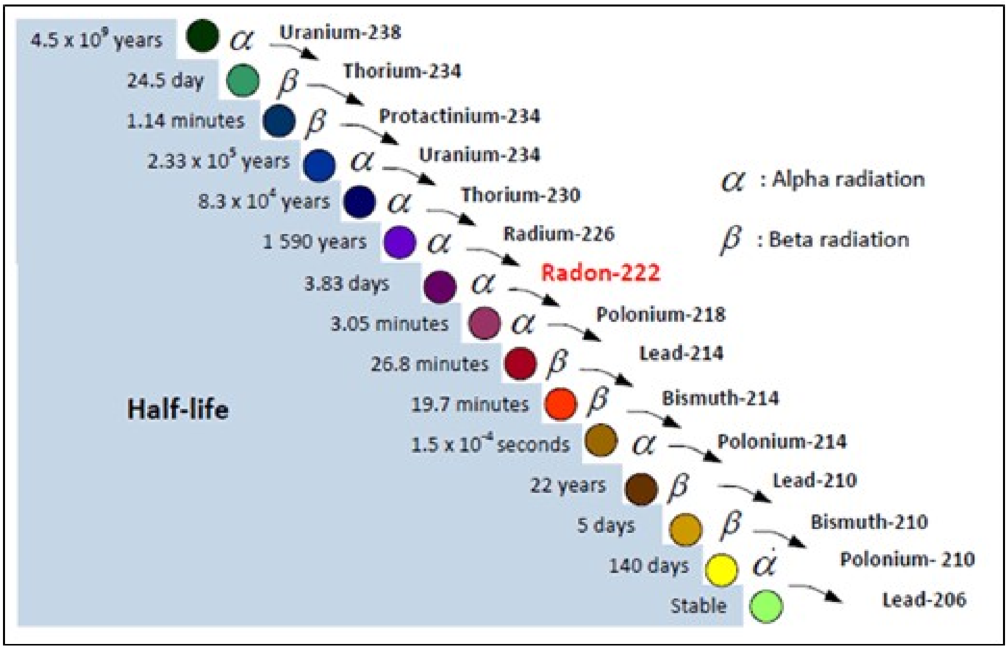

Figure 1. Uranium-238 decay chain [56].

Table 1. Characteristics of radon [57].

Symbol	Rn
Atomic Number	86
Atomic Weight	222
Melting Point	−71.0 °C (202.15 °K, −95.8 °F)
Boiling Point	−61.8 °C (211.35 °K, −79.24 °F)
Number of Protons and Electrons	86
Number of Neutrons	136

Table 1. *Cont.*

Symbol	Rn
Class	8A group (Noble)
Crystal Structure	Cubic
Density	9.73 g/cm^3
Half-Life	3.82 day

Following the discovery of radon (^{222}Rn) gas, whose original content comes from the ^{226}Ra isotope and which has a very short half-life of 3.82 days, studies on the radioactivity of this gas began to attract attention [58,59].

2.1. Radon Gas Sources

2.1.1. Radon from Soil and Rocks

The amount of uranium found directly affects the amount of radon found. Since the uranium concentration in the soil varies, the radon concentration also varies [60,61]. Radon gas spreads into the environment in close relation to the geological structure in the region. It can accumulate in buildings and be found in rocks and soil in different amounts [62]. One of the sources of radon gas entering buildings is the soil and rocks on the land where we find these buildings. In soils and rocks rich in radium, uranium, and thorium, enabling the formation of radon gas, radon gas leaking through existing cracks tends to escape into the atmosphere [63,64].

Figure 2 illustrates the uranium exposure in different types of bedrock [65]. Figure 2 also compares the uranium exposure's direct effect on radon gas formation in these types of bedrock, and it is indicated that granite- and clay-based bedrocks are rich in uranium; carbonate-based (limestone) bedrocks have moderate levels of uranium; and basalt- and sandstone-based bedrocks are low in uranium.

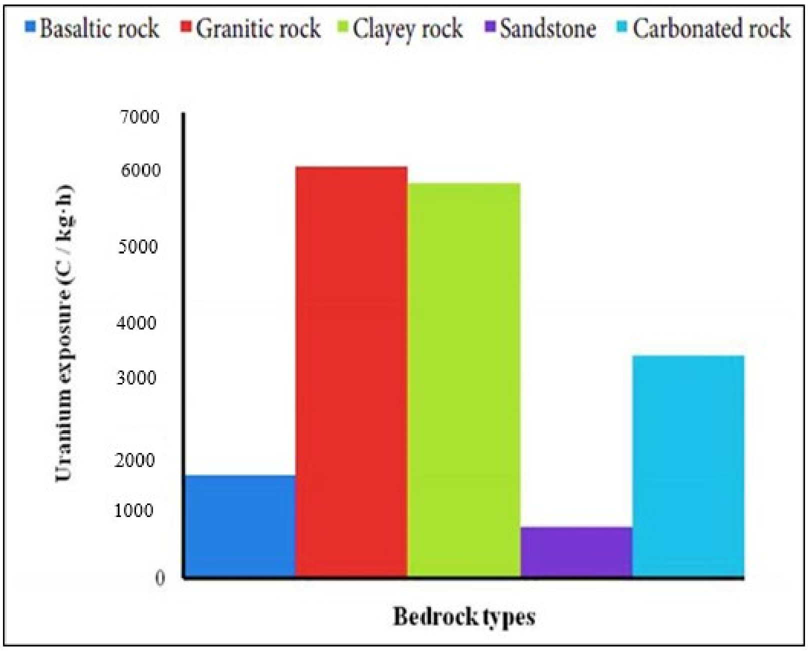

Figure 2. Uranium exposure in different bedrock types [65].

Hungary's highest radon concentration value (yearly average of 227 $\pm$ 10 BqL^{-1}) was determined in gneiss rock, which was formed due to the metamorphism of old granitic rocks [66]. In a study in Portugal [67], granite rocks exhibited the highest radon gas concentration (2 to 73 Bqkg^{-1}). It was stated, especially regarding igneous rocks, that uranium formation was more common in crystalline rock types such as granite [68]. As a result of Ref. [68], it was reported that the radionuclide concentration values ranged from 3 ± 2 to 97 ± 1 Bqkg^{-1}. It was reported that Galicia, an autonomous region in the northwest of Spain, has the highest indoor radon concentration in the entire country due to the granitic structure of the underground layer there [69]. Factors such as the soil pore size, permeability, humidity rate, temperature, and uranium content have an effect on the emission of radon gas [70–72]. For example, radon gas can easily rise to the surface in highly permeable soils. The most important geological source of increased radon gas emissions was emphasized as active tectonic faults, characterized by the high permeability of the soil and rock [73]. Studies [74–76] have reported that the radon levels increase in fault zones in a short period, ranging from a few hours to a few weeks, before the occurrence of an earthquake. Oh and Kim [77] stated that radon level anomalies in Japan can be used as a useful tool to determine the precursors of earthquakes.

Figure 3 illustrates a schematic diagram explaining the stages of radon gas development from its underground formation to its rise to the surface. Accordingly [78], free radon gas is formed due to the decay of radium in the underground layer in the first stage. During this stage, factors such as density and humidity exacerbate nuclear recoil, and consequently, radon gas is released through microcracks in the rocks. In the second stage, radon gas, which became free in the initial stage, migrates collectively and moves into the atmosphere under soil properties such as water saturation and permeability.

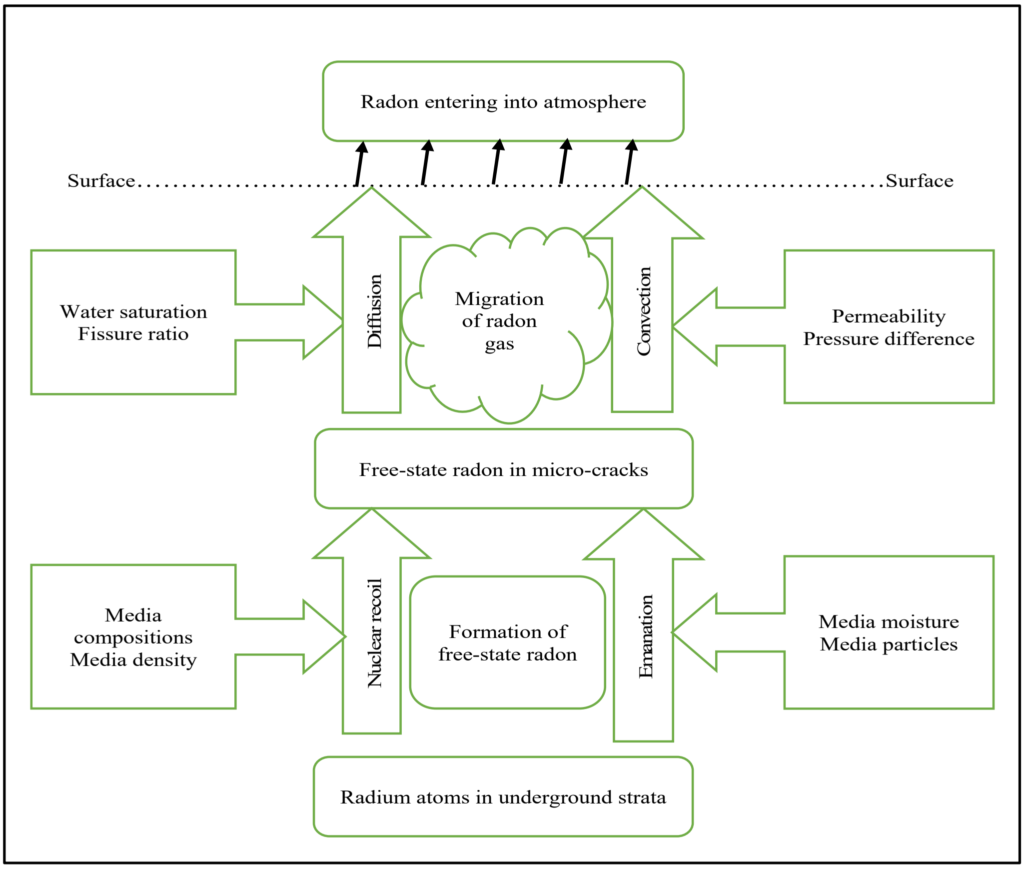

Figure 3. Migration of radon gas from underground to the surface [78].

2.1.2. Radon from Water

Drinking water is obtained from water sources and groundwater sources such as wells and boreholes in many countries. Groundwater is obtained from geological formations called aquifers, and due to the radium-rich soil and rocks they come into contact with or pass through, groundwater radon concentrations can be high [79,80]. However, the radon concentration in surface water is generally lower due to its release into the air compared to groundwater, where granite, sand, and sediments are present [81]. With an increase in the water temperature, the amount of radon gas released into the environment also increases [82]. The health hazards associated with high concentrations of radon in drinking water mostly result from inhaling radon in indoor air, tap water, and, to a lesser extent, direct ingestion. In studies conducted on this subject in the USA [83], higher levels of radon gas were observed in small and special-purpose well sources than in large public water sources. The reason reported was that small and special-purpose well resources were generally located in low-capacity aquifers containing uranium-containing granite, metamorphic rocks, or fault zones, while the large water resources used by the public mostly used gravel and sand aquifers with lower levels of uranium content.

2.1.3. Radon from Air

Radium from the soil constitutes the main source of radon gas in the air [84]. The radon emissions into the air are higher than into water [85]. Furthermore, radon gas in the natural gas used for heating or cooking in houses can disintegrate and mix with the air, increasing the radon concentration. It has been stated that precautions could be taken against this situation through ventilation [82].

2.1.4. Radon from Construction Materials

Natural, artificially manufactured, and by-product construction materials contain varying amounts of naturally occurring radionuclides in the ^{238}U and ^{232}Th decay chains. The gamma rays among these radionuclides constitute external exposure (an outdoor radiation source). On the other hand, the alpha rays released from radon and its decay products, which can enter the body through respiration as a result of its release, constitute internal exposure (an indoor radiation source) for building occupants [86]. In addition to the qualities of the soil under buildings, construction materials and construction methods are important factors, especially in indoor radon concentrations [87–89]. At this point, the radon permeability of the construction materials is considered a vital factor for determining the radon level inside a building, highlighting the entrapment of radon gas inside after it enters rooms through cracks in the floor and foundations [90]. Many factors, such as the $^{238}U/^{226}Ra$ content, meteorological and climatic parameters, and ventilation rate, affect the level of radon gas emitted by construction materials [91]. Studies (e.g., [84]) have shown that the contribution of construction materials to indoor/in-building radon concentrations was 10 Bqm^{-3}. Considering that the annual average radon concentration in the world is approximately 40 Bqm^{-3} [92], the contribution of construction materials to indoor/in-building radon concentrations was around 25% [93]. In European Union countries, this contribution is estimated to be 10–20 Bqm^{-3} [28,94]. Materials that cause radon gas emissions include aluminous shale, granitic rocks, porphyry, tuff, pozzolana, lava, fly ash, phospho-gypsum, phosphorus slag, tin slag, copper slag, aluminum, and steel production residues [93]. Studies [95–99] have also been carried out on the radon gas content and emission of commonly used construction materials such as concrete, cement, brick, and aggregates, along with these materials. Table 2 presents the ^{226}Ra concentration values of the construction materials used in different countries. It was observed that gypsum and granite had the highest values (in the USA and Russia, respectively), while the ^{226}Ra concentration values of fine aggregates (sand), cement, and concrete were at the lowest levels (in Russia, Sweden, and Norway, respectively) [82].

Table 2. ^{226}Ra concentration values of construction materials in different countries [82].

Construction Materials	^{226}Ra Concentration (Bq/kg)	Country
Cement	44.4	Russia
	55.5	England
	44.4	Sweden
Concrete	26	Norway
	66.6	Germany

Table 2. *Cont.*

Construction Materials	^{226}Ra Concentration (Bq/kg)	Country
Brick	51.8 18 55.4 96.3 96.2 104	England Poland Russia Sweden Germany Norway
Gypsum	1480 580–740 777 15.5–54.5	USA Poland England Germany
Fine aggregates (sand)	23.3	Russia
Coarse aggregates (gravel)	102 48.1 51.8	Finland Sweden England
Granite	96.2 111 88	Germany Russia England

In radon concentration measurements carried out in closed environments in Iraq, it was reported that radon gas accumulated in unventilated rooms and reached an average level of 440 Bqm^{-3}, while the average radon concentration value was reduced to 17 Bqm^{-3} in ventilated rooms [100]. Xie et al. [101] also examined the relationship between the indoor radon gas concentration and ventilation. Accordingly, it was determined that (i) the radon concentration had a linear increase in a closed environment within the first 2 h; (ii) when the environment was kept closed for 8 h, a radon concentration of 434 Bqm^{-3} was reached in dynamic equilibrium; (iii) the upper and middle parts of the indoor environment had a lower radon concentration than the lower and surrounding areas; and (iv) if the indoor environment was ventilated for 20 min (a stabilization period), the radon concentration value decreased down to 150 Bqm^{-3}.

In a study in which long-term radon time series were analyzed in 14 rooms and offices to investigate the factors affecting the indoor radon concentration in high-rise buildings [102], it was found that the main factor affecting the radon concentration dynamics for rooms with low human activity was the change in the temperature difference between outdoor and indoor air. It was also stated that for rooms with normal human activity, the radon concentration and the coefficients of variation in this value depended on the activity of those living in the building at certain times of the day. In most cases, a sub-slab or sump depressurization system with an active ventilation technique was more effective in achieving a significant and sustained radon reduction than passive methods such as sealing, membrane, blocks, beams, simple ventilation, or filtration [103].

Construction materials with a rich uranium content are considered potential radon gas emitters [104–106]. In addition, parameters such as the amount of radium in the materials, the height of the building, and the permeability of the ground of the building are among the factors affecting the radon gas level [107,108]. An increase in health problems, especially lung cancer, is observed as a result of constant exposure to high amounts of radon gas in closed environments such as houses and workplaces. Therefore, measures must be taken to reduce the radon concentration to lower levels [10]. Figure 4 illustrates the mechanisms of the entry of radon gas into buildings [109].

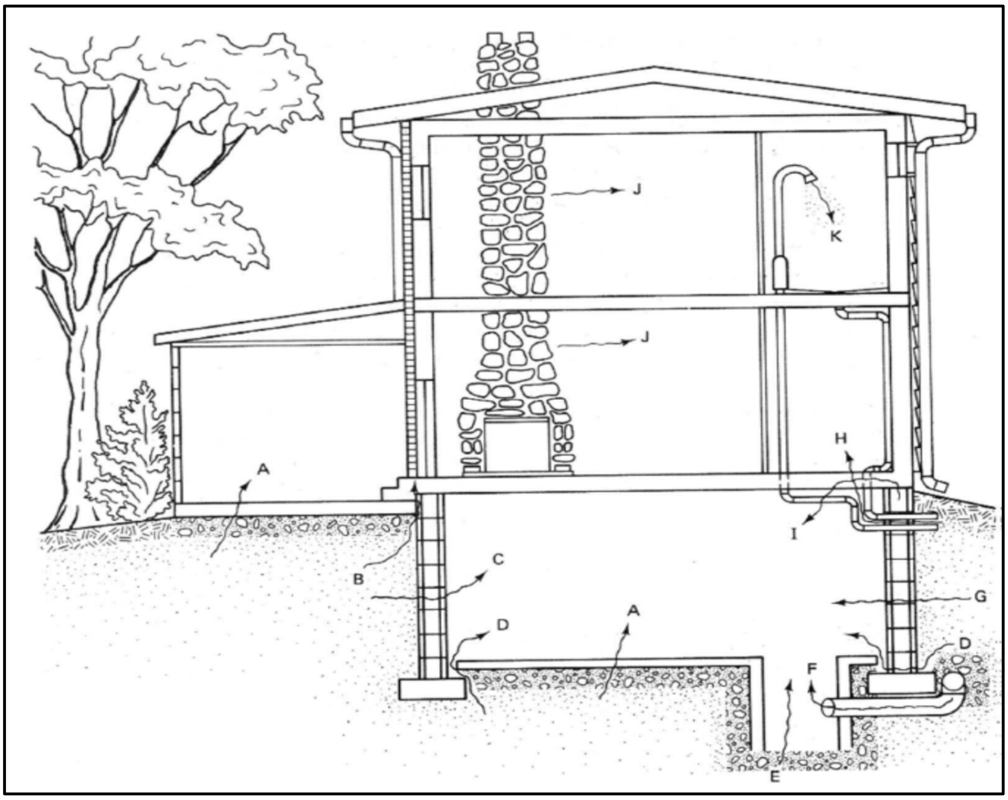

Figure 4. Mechanisms of entry of radon gas into buildings; A, cracks in concrete slabs; B, spaces behind brick veneer walls that rest on hollow block foundations; C, pores and cracks in concrete blocks; D, floor–wall joints; E, exposed soil, as in a sump; F, weeping (drain) tile, if drained to open sump; G, mortar joints; H and I, cracks at the junction/corner points of pipes and concrete blocks; J, building materials, such as certain rocks; K, water (from some wells) [109].

As seen in Figure 4, radon gas enters and accumulates in buildings mainly through cracks and gaps in the ground, connection points in the structure, and wall cracks.

It should be noted that although radon is a natural radioactive gas, an increased radon level in residential buildings is not a natural phenomenon and is an undesirable consequence of poor building design, poor materials, and poor ventilation. Radon is considered to be one of the major causes of indoor air pollution [110]. Nowadays, there is an increasing demand for certificates confirming safe radon levels in buildings [111].

2.2. Radon Concentration Limits

In 1956, studies on radon gas measurement in indoor environments were initiated for the first time in Sweden [112]. However, although very high concentration values were obtained in some locations, this issue was not focused on much, considering it was a region-specific measurement [61]. Since the 1980s, studies on radon gas emission and measurement methods have accelerated worldwide. Researchers have attempted to determine the limit values both on a country basis and across international organizations to control the concentration of radon gas in indoor environments. If these limit values are exceeded, precautions are recommended to reduce the radon gas concentration. The World Health Organization (WHO) has determined the annual average radon concentration limit for member countries to be 100 Bqm^{-3}. However, if this value cannot be reached under specific country conditions, the limit value is requested not to exceed 300 Bqm^{-3} [28]. The European Commission (EC) and the International Commission on Radiological Protection (ICRP) have set the recommended limit values for indoor environments as 300 Bqm^{-3} and 1000 Bqm^{-3} for houses and workplaces, respectively [113,114]. Within the scope of the International Atomic Energy Agency Essential Safety Standards (IAEA-BSS), the recommended values for radon gas have been determined as 200–600 Bqm^{-3} [94]. In Turkey, according to the Turkish Atomic Energy Agency (TAEA) Radiation Safety Regulation [115] the limit values have been accepted as 400 Bqm^{-3} in houses and 1000 Bqm^{-3} in workplaces [20,22,116].

Table 3 presents the national radon concentration limit values of countries determined by WHO [117]. The data in this table are for the year 2019 and are subject to regular updates. As can be seen in Table 3, the radon gas limit values vary from country to country. The countries that apply the lowest limit values for both houses and workplaces on radon concentration (<100–200 Bqm^{-3} for houses, <100–400 Bqm^{-3} for workplaces) are the Netherlands, Norway, Denmark, Sweden, Canada, the United Kingdom, and Latvia. In many countries, especially France, Germany, and Spain, the limit value (<300 Bqm^{-3}) has been determined for houses and workplaces. The United States has set radon limit values that are very low (<148 Bqm^{-3}) for houses and very high (<3700 Bqm^{-3}) for workplaces. While a limit value (<300 Bqm^{-3}) has been determined for houses in China and Argentina, no limit value has been determined for workplaces.

Table 3. Radon limits accepted by countries [117].

Country	Limit Values (Bqm^{-3})	
	House	Workplace
Holland	<100	<100
Norway	<100	<100
Denmark	<100	<100
Sweden	<200	<200
Canada	<200	<200
The United Kingdom	<200	<300
Latvia	<200	<400
Austria	<300	<300
Belgium	<300	<300
The Czech Republic	<300	<300
Finland	<300	<300
France	<300	<300
Germany	<300	<300
Greece	<300	<300
Spain	<300	<300
Portugal	<300	<300
Bulgaria	<300	<300
Bahrein	<300	<300
Australia	<200	<1000
Belarus	<200	<1000
Georgia	<200	<1000
Brazil	<300	<1000
Turkey	<400	<1000
Serbia	<400	<1000
Argentina	<300	-
Chinese	<300	-
The United States of America	<148	<3700

2.3. Effects of Radon Gas on Human Health

Radon gas easily leaks from the Earth's crust and decays into short-lived particles called radon products. These short-lived particles emit alpha rays [118]. Since these rays are electrically charged, they can attach to dust particles, especially in a closed environment. These dust particles can also be easily inhaled and stick to the lungs [119,120]. As radon gas disperses into the atmosphere, solid radon products are stored in water and soil and are involved in the food chain [20,121].

Radon gas from soil, rocks, water, and construction materials constantly migrates through cracks/voids inside buildings [122,123]. Ultimately, radon (^{222}Rn) gas is released from the material surface into the ambient air with a half-life of 3.82 days and remains in the indoor and outdoor air for a certain time period [124]. In the outdoor environment, radon gas is rapidly diluted, so it does not affect human health [125]. However, when radon gas enters closed environments such as houses or school buildings, it can accumulate and reach levels that are harmful to human health [126]. As stated in the report published by WHO [28], when radon gas reaches the lungs through breathing, the ionizing alpha rays (particles) formed by radon's short-lived decay products (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po) interact with biological tissue and cause DNA destruction [127]. This constitutes (DNA destruction) the first link in the chain of events leading to cancer.

Radon gas is considered the main factor responsible for lung cancer among never-smokers [128]. Radon gas, also known as the "invisible killer", is considered the second most important cause of lung cancer after smoking [28,107,129]. In a World Health Organization report [28], it was stated that radon-caused lung cancer cases were also encountered among smokers due to the interaction between radon and smoking. As a matter of fact, it is estimated that smokers are 25 times more at risk from radon than non-smokers.

Lung cancer is one of the most common and aggressive cancers worldwide [130] and is known as the leading cause of cancer-related deaths [131,132]. It was also announced that lung cancer was the first most common cancer type in men and the third most common cancer in women in the world [133]. The first association between radon exposure and lung cancer risk dates back to 1924, when an autopsy report revealed that lung cancer was the cause of death in a radon-exposed miner [134]. The results of scientific studies conducted in subsequent years confirmed that a high concentration of radon gas in indoor environments might be associated with lung cancer [135–137] and the tumor mutation load [138]. Nyhan et al. [139] stated that radon-derived particle radioactivity was associated with increased blood pressure and cardiovascular diseases. Loiselle et al. [140] reported that long-term radon exposure affected genes and triggered malignant transformations in human bronchial epithelial cells (the cells enveloping the inner and outer surfaces of the body). Walczak et al. [141] stated that the DNA damage in peripheral lymphocytes increased in parallel with the increase in radon concentration in closed environments. Papatheodorou et al. [142] reported that hypertensive pregnancy disorders occurred as a result of radon exposure, especially in young pregnancies. According to WHO [143], radon gas is responsible for 3–14% of lung cancer cases in the world. For every 100 Bqm^{-3} increase in the long-term average radon concentration, the risk of lung cancer increases by approximately 16%. Additionally, in 2019, there were 84,000 deaths worldwide due to lung cancer caused by indoor radon gas [144]. It was announced that radon gas in indoor environments was responsible for approximately 20,000 lung cancer deaths annually throughout the European Union and 14% of all lung cancer cases in Ireland were caused by radon [145]. It is known that radon causes 20,000 deaths per year in the United States and approximately 300 deaths per year in Norway [128].

2.4. Possible Precautions against Radon

Precautions that can be taken to reduce the risks and hazards caused by radon are given below [20,28,57,121,146–152]:

- First of all, public-level awareness should be raised on radon gas. Efforts should be made, especially in constructing new buildings and improving existing ones.
- Public awareness should be raised by creating public health programs at the national level to reduce the radon risk.
- It is also necessary to identify the geographical regions with the highest radon exposure at the national level, ensuring a higher focus on these regions.
- The soil insulation process should be carried out properly, especially for basement floors in buildings.
- It should be ensured that the airflow moves from inside the building to the ground.
- Radioactivity analyses and dose evaluations of construction materials should be carried out scientifically, and construction materials with higher values than the recommended limit values should not be used in construction.

- The radon gas leaking into buildings is trapped inside. Therefore, attention should be paid to ventilation.
- Frequent measurements should be made for the radon gas exposure that may arise from water, soil, and air in residential areas, and precautions should be taken accordingly.
- The indoor radon concentration can be reduced, especially by adding a covering layer of sufficient thickness to interior walls, floors, and ceilings.

2.5. Radon Gas Activity Concentration Measurement Methods

Several methods have been developed regarding radon measurement techniques so far. These methods [55,64,116,153–159] involve measurement with activated charcoal, ionization chambers, the collector method, Lucas cells, electrostatic collection, solid-state trace scraping detectors, electret ion chambers, and continuous radon monitors. The basic principle of most of these methods is based on counting the alpha particles resulting from radon's decay products. Since radon gas is a tasteless, odorless, colorless, and radioactive gas, it cannot be detected using chordotonal organs. Measurements can only be made using specially developed techniques [160–166].

Radon gas activity concentration measurements are categorized into two groups, as described below: active and passive measurement methods [84,167].

2.5.1. Active Measurement Method

Instant radon measurements can be made using the active measurement technique, the quickest method used to measure the radon concentration in indoor environments [168]. The calculation is performed by taking an air sample from the measurement environment and counting the amount of radiation in this sample using a radiation counter. Examples of instruments used in the active radon gas measurement method are scintillation cells, electrostatic collectors, and filters. The most important characteristic of the instruments utilized in this method is that radon concentration in soil, water, air, and construction materials can be measured with the necessary equipment support (water kit, soil prop) [169,170]. However, this method is generally used in short-term measurements and sampling studies. It is not preferred for measuring the atmospheric radon concentrations inside buildings. The reason for this is that radon gas concentration can be significantly affected by factors such as temperature, humidity, and pressure, leading to notable changes in short periods [36,171].

2.5.2. Passive Measurement Method

In this method, the long-term radon gas concentration can be determined, with nuclear trace detectors placed in the measurement media [172]. The passive measurement method is considered a method that can be used to obtain an average value for radon gas [173–175]. Measurements can be made using this method daily, monthly or on a seasonal or annual basis. The nuclear trace detectors used in this method generally consist of plastic film layers such as polycarbonate, cellulose acetate, and allyl diglycol carbonate [176,177]. The measurement process is based on the principle of counting the invisible traces left by the alpha particles hitting these plastic layers using a microscope and clarifying them using the chemical etching method [21,72]. This method can be used to determine the radon gas concentration in indoor environments, mines, underground metro stations, and caves [14,20]. Solid-state nuclear trace detectors (cellulose nitrate (LR-115) and allyl diglycol carbonate (CR-39)) are often preferred in the passive measurement method [34,82,178–182].

Table 4 presents the most preferred and used radon gas measurement devices by the member countries of the World Health Organization [28] and the qualifications of the applied methods. As seen in Table 4, the alpha trace detector is a passive method with both a low cost and a sampling period of up to 12 months.

It is noteworthy that continuous radon monitoring, especially using an active method, has a high cost. However, the sampling period of the method can be within a wide range from 1 h to several years. In a study [183] comparing the radon concentration values according to different radon monitoring approaches (active and passive methods), it was reported that the most important consideration is the reliable calibration of radon devices and that the measurement should be designed rationally and great precautions should be taken in reporting the values.

Table 4. Radon gas measurement devices and characteristics of the applied methods [28].

Detector Type	Method Name	Uncertainty * Range (%)	Typical Sampling Period	Cost
Alpha Trace Detector	Passive	10–25	1–12 months	Low
Activated Charcoal Detector	Passive	10–30	2–7 days	Low
Electret Ion Chambers	Passive	8–15	5 days–1 year	Medium
Electronic Integrated Device	Active	~25	2 days–a few years	Medium
Continuous Radon Monitor	Active	~10	1 h–a few years	High

* Uncertainty range (%) is for optimum exposure time with exposure up to approximately 200 Bqm^{-3}.

3. Radon Gas Measurement in Concrete and Buildings

It is also possible to categorize the studies on radon gas concentration measurements in concrete and buildings into two groups, described below: measuring the radon exhalation rate and indoor radon concentration.

3.1. Radon Exhalation Rate

Exhalation is defined in soil science as the process of the escape of radioactive gases from the surface layers of soil or loose rocks due to the decay of radioactive salts. The exhalation of radioactive gases, primarily radon and thoron, increases with the soil temperature and normally exhibits a single daily maximum around noon. A reduction in atmospheric pressure normally increases release, while freezing the surface soil layers often greatly reduces it [184].

The radon exhalation rate is a value measured using active methods and a continuous radon gas monitor and is also referred to as "radon flux" in the literature [185,186]. The radon exhalation rate is measured after hermetically sealing the sample in a container and taken as the growth of the radon activity as a function of time [187]. The emission rate from a solid sample with a well-defined surface is defined as the surface emission rate in Bqm^{-2} h^{-1} or Bqm^{-2} s^{-1}. Radon emissions are the flux of radon emitted from existing material surfaces that are affected by material geometry and boundary conditions. On the other hand, the radon potential is defined as the concentration of radon produced inside the material and ready to be transported through its pores [188]. The exhalation rate is evaluated in Bqkg^{-1} h^{-1} if the sample is in powder form [189–191].

There are a few studies on measuring the radon exhalation rates from concrete surfaces. In a study [192] in which the radon exhalation rates of concrete samples were determined periodically for 6–8 years after the casting of the concrete, the radon exhalation rate was stated to depend on the age of the concrete and changed significantly 1.5 times over in the first 6–12 months after casting. After this period, little change was observed in the emission rates. It was also emphasized that low humidity conditions significantly reduced the radon exhalation rate of the concrete. A study [193] examining the effect of the concrete composition and the production process on the radon exhalation rate found strong positive correlations between the radon release calculated and the evaporation rate and water/cement ratio. Additionally, a negative correlation was observed for the compression strength of the concrete. It was concluded that the void structure in the concrete affected the radon exhalation rate. Studies [192,193] conducted in the Netherlands changed the perspective in this field in terms of both the measurement method for the radon exhalation rate of concrete and the effects of the concrete components on this rate.

In another study [194], in which the change in the radon exhalation rates from concrete surfaces of different ages was examined, the radon exhalation rate was observed to decrease with the age of concrete blocks, and the rate increased after the immersion of the blocks in water. The gradual dehydration of the concrete, which reduces the water content in the pores and thus reduces the possibility of radon retention within the pores and the possibility of radon emission, was considered responsible for this situation. In a study [195] investigating the effects of the cracks and voids in the concrete on the radon exhalation rate, the total radon released from the concrete blocks was found to be the same regardless of the diameter of the voids and the number of opened voids. It was emphasized that the surface area of the concrete blocks did not affect the total radon emission.

In a study [196] examining the radon emissions from concrete surfaces and the effects of the curing time, pulverized fuel ash replacement, and age, the radon emission rates from 48 concrete blocks were monitored for more than one year. A total of 50% of the mixtures were prepared with two types of pulverized fuel ash substitutes, and 50% were prepared without the use of fuel ash. The curing periods were determined as 1, 3, 7, and 28 days. Different emission rates were reported to be linked to the role of the superficial and internal pores in the concrete. It was also emphasized that the rate of radon emission tended to decrease with the age of the blocks for curing periods of 1, 3, and 7 days; however, it began to increase for a curing period of 28 days, and all of this could be rationalized in terms of the gradual age-based drying of the concrete. Finally, the exact impact of pulverized fuel ash on radon emission rates has not yet been determined. In another study [195] where pulverized fuel ash was substituted for cement in concrete, the radon emission rate was reported to reduce thanks to pulverized fuel ash, and the recommended percentage of optimum ash to use was 15%. Studies [194–196] conducted in Hong Kong have been considered important references in terms of the pore and crack structure of concrete and the effect of materials such as pulverized fuel ash used in concrete on the radon exhalation rate.

The radon exhalation rates measured in a range of construction materials commonly used in Greece varied between values measured globally, with the highest rate after granite seen in concrete (0.037 ± 0.022 Bq kg^{-1} h^{-1}), revealing the primary source of radon in typical Greek construction materials [197]. As a result of a study on the moisture dependence of the radon exhalation rate of concrete [198], the radon exhalation rate was found to increase almost linearly up to a moisture content of 50% to 60%. The radon exhalation rate was stated to decrease very rapidly for higher moisture contents, reaching a maximum of 70% to 80%.

Kovler et al. [199] found that the fly ash dosage in cement paste had a limited effect on the radon exhalation rate if the hardened material was relatively dense. In addition, the radon flux of fly-ash-added cement pastes was lower than that of pure cement paste. With this study, our perspective on the effect of fly ash on the radon exhalation rate has deepened. In their research on low-porosity materials such as concrete, Fournier et al. [200] determined that both the radon concentration and exhalation rate increased significantly up to a high volumetric water content (40%). This significant increase in concentration and release is explained by the dominant role of emanation compared to radon emission. Righi and Bruzzi [201] obtained a similar result in that this value in concrete was observed at a very low level (0.0089 ± 0.0007 Bq kg^{-1} h^{-1}).

In a study [202] evaluating the radiological hazards in construction materials used in Elazığ (Turkey), both the radon concentration (297.06 Bqm^{-3}) and radon exhalation rate (4.81 Bqm^{-2} d^{-1}) of an aerated concrete sample were lower than those of other construction materials. The reason for this was explained to be the formation of more air bubbles, which prevent the spread of radon during the aerated concrete production process. Equally, de Jong et al. [203] found that the amount of cement was the main contributor to the amount of radon emitted in all mixtures. It was reported that reducing the amount of Portland or blast furnace slag cement in the mixtures caused this emission factor to increase gradually, just like the amount of water in fresh paste at a constant cement dosage. Despite strongly affecting the porosity of the mixtures, adding an air-entraining agent or replacing river gravel with recycled aggregates did not significantly affect the radon emission. It was stated that the capillary porosity of concrete played a dominant role in radon emission.

In a study [204] where the radon exhalation rate of certain construction materials used in Egypt was measured, the radon exhalation rate of concrete was 14.33 Bqh^{-1}, which was relatively lower than that of other construction materials. In a study conducted in Iran [205], this value of concrete was found to be 0.23 ± 0.03 Bqm^{-2} h^{-1}, and it was reported that no health hazard result was obtained.

Chauhan and Kumar [206], on the other hand, recommended adding up to 30% silica fume to the cement to obtain a lower emission coefficient and exhalation rate. As a result of a study [207] investigating the radon resistance potential of concrete blended with rice husk ash, the radon emission rates of rice-husk-ash-substituted concrete were reported to be lower than the control concrete. It was also suggested that up to 30% of the cement be replaced with rice husk ash to reduce radon emissions. Georgescu [208] reported that the exhalation rate decreased with an increase in the concrete density and a decrease in the water/cement ratio. It was found that radon concentrations were higher in a room made of concrete prepared with cement with limestone and fly ash additives than in other types of concrete prepared with cement and slag additives, regardless of the age of the concrete. It was emphasized that cement- and slag-added concrete had less air and water permeability and exhibited a lower porosity, exhalation rate, and indoor radon concentration than other types of concrete.

Kumar and Chauhan [209] stated that the radon exhalation rate was stated to decrease with a decrease in the porosity of the concrete and an increase in the moisture content, and this rate varied according to the age of the concrete. Studies [206,207,209] conducted in India on the effects of mineral additives such as silica fume and fly ash, which are widely used in concrete, on radon exhalation rates were examined in more detail and introduced into the literature. Trevisi et al. [210] prepared concrete samples consisting of the same components but utilized different amounts of mineral additives and emphasized that the radon exhalation rate measurements were not affected by the shape and size of the samples. On the contrary, the ratio between the surface of the samples and the volume of the closed chamber was found to be an important parameter with respect to the overall uncertainty. It was stated that the exhalation rate values were scattered, from approximately 1.6 Bqm^{-2} h^{-1} to 13 Bqm^{-2} h^{-1}, and that these values were compatible with the results on mineral-added concrete measured in many European countries.

A 30–35% decrease in the radon gas exhalation rate of fly-ash-added concrete samples was observed with a relative humidity below 80–85% [211]. As a result of a study [210] presenting an updated database on the natural radioactivity in construction materials in Europe, an average radon exhalation rate of 17 Bqkg^{-1} h^{-1} was obtained for concrete. Hatungimana et al. [212] determined that the addition of silica fume was reported to reduce the radon concentration and surface radon exhalation rate. In the same study, the reduction in the surface radon exhalation rate due to silica fume ranged between 23% and 43%, while there was an increase of up to 15% in fly-ash-containing mortar mixtures compared to the control mortar mixture. This study has now taken its place in the literature as a reference study against which more detailed evaluations are made regarding the radon exhalation rate results in blended cement pastes.

A study [213] conducted in Ecuador argued that the radon exhalation rates of construction materials ranged from 0 to 7.83 Bqm^{-2} h^{-1}. While the highest surface exhalation rate was detected in granite samples, clay bricks exhibited the minimum radon exhalation rate. Concretes had a low radon exhalation rate value of 1.148 Bqm^{-2} h^{-1}. As a result of a study in which the effect of the temperature difference between concrete and indoor air and the effect of the water content in the concrete on radon emissions were examined [214], in concrete with a 0% water content, the heat generated due to the temperature difference between the concrete and indoor air was reported to be able to increase the radon exhalation rate 2.6 times over. In addition, an increase in the water content from 0% to 10% was stated to cause the radon exhalation rate to increase 3.4 times over.

Table 5 summarizes many of the studies on radon exhalation rate (RER) measurements conducted worldwide, which are important in presenting up-to-date results.

Table 5. Radon exhalation rate (RER) measurement results, units, and sample types.

City/Country Name	RER	RER Units	Sample Types	Ref. No
The Netherlands	$0.1–1.3 \times 10^{-5}$	Bq kg^{-1} s^{-1}	Concrete	[192]
The Netherlands	3.9 ± 0.2	Bq/m^2.h	Concrete	[193]
Hong Kong	6–11	mBq m^{-2} s^{-1}	Concrete	[194]
Hong Kong	$10.2–10.9 \times 10^{-6}$	Bq kg^{-1} s^{-1}	Concrete	[195]
Hong Kong	4–14	mBq m^{-2} s^{-1}	Concrete	[196]
Greece	0.037 ± 0.022	Bq kg^{-1} h^{-1}	Concrete	[197]
The Netherlands	$5 \times 10^{-11}–2 \times 10^{-8}$	m^{-2} s^{-1}	Concrete	[198]
Israel	∼3	mBq m^{-2} s^{-1}	Cement-paste-containing fly ash	[199]
Austria–France	0.05	mBq m^{-2} s^{-1}	Concrete	[200]
Italy	0.0089 ± 0.0007	Bq kg^{-1} h^{-1}	Concrete	[201]
Turkey	4.81	Bqm^{-2} d^{-1}	Aerated concrete	[202]
The Netherlands	$5.7 \pm 0.6–8.1 \pm 0.3$	Bq kg^{-1} s^{-1}	Portland cement	[203]
Egypt	14.33	Bq h^{-1}	Concrete	[204]
Iran	0.23 ± 0.03	Bqm^{-2} h^{-1}	Concrete	[205]
India	$180 \pm 10–510 \pm 30$	mBq/m^2 h	Silic-fume-modified concrete	[206]
India	0.5–3.4	mBq/m^2 h	Rice-husk-ash-blended cement	[207]
India	0.3–0.5 (for fly ash) 0.17–0.5 (for silica fume)	Bq/m^2 h	Silica-fume- and fly-ash-modified concrete	[209]
Europe	1.6–13	Bqm^{-2} h^{-1}	Concrete	[210]
Sweden	25.48	Bq/m^2 h	Concrete	[211]
Turkey	361 ± 19 (for fly ash) 218 ± 14.7 (for silica fume)	mBq m^{-2} h^{-1}	Silica-fume- and fly-ash-modified mortar	[212]
Ecuador	0–7.83	Bqm^{-2} h^{-1}	Construction materials	[213]
China	0.76–2.59	mBq m^{-2} s^{-1}	Concrete	[214]

Based on the information from the literature summarized above, the parameters affecting the radon exhalation rate of concrete can be visualized, as seen in Figure 5.

Although studies have been conducted on the radon exhalation rate, some researchers (e.g., Ref. [97]) have also stated an urgent need for an improved protocol for standardizing radon exhalation rate measurements of construction materials using widely accepted and reliable measurement techniques. In this protocol, researchers recommend specifying many important parameters such as the sample preparation, shape and size of the samples, the ratio between the volume of the accumulation chamber and the sample, the units for expressing the results, and the density measurement.

3.2. Indoor Radon Concentration

The amount of radon gas released from concrete buildings can also be assessed by measuring the radon concentration inside buildings (indoor environments) as determined using nuclear trace detectors. In the following paragraphs, the findings from studies conducted around the world on the subject are summarized, and then the studies conducted in Turkey are mentioned.

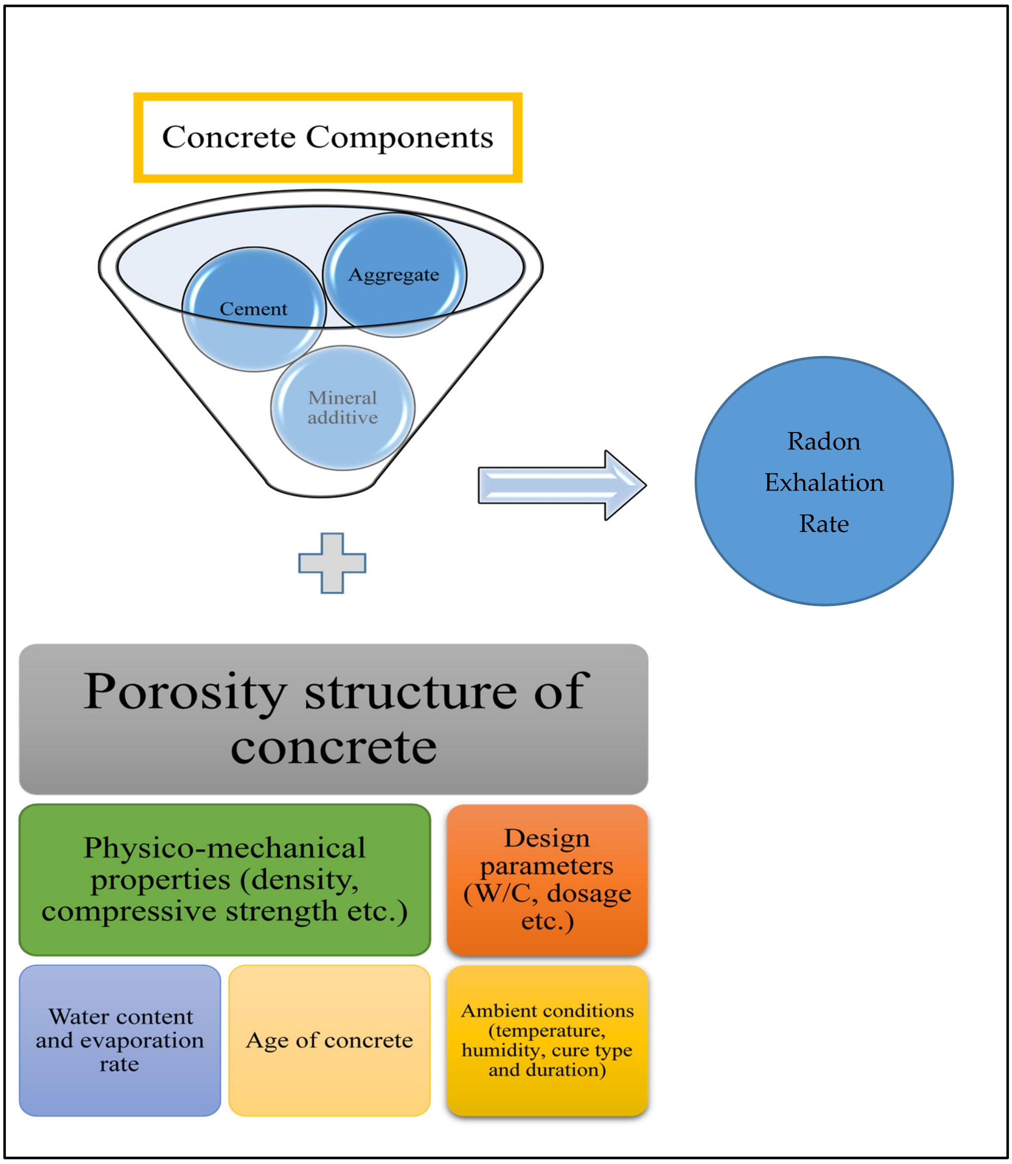

Figure 5. Parameters affecting the radon exhalation rate of concrete.

As a result of studies [215,216] conducted in Hong Kong on reducing the indoor radon concentration by using lightweight concrete in high-rise buildings, when lightweight concrete was used instead of normal concrete, the possible reduction in the indoor radon concentration was calculated to be greater than 15 Bqm^{-3}. Considering an average indoor radon concentration of approximately 45 Bqm^{-3} in Hong Kong, lightweight concrete was emphasized as a simple and economical solution to reduce indoor radon concentrations. Indoor radon measurements of high-rise lightweight concrete has brought a different perspective to the literature. According to the results of indoor radon research conducted in Montenegro [217], the average radon concentration was 26.4 Bqm^{-3}, and the average indoor radon level was highest in detached houses made of bricks and lowest in apartment houses made of concrete and brick with plastered walls. In a study [218] in which the radon levels and entry mechanisms were examined experimentally and theoretically in a house under a Mediterranean climate in Barcelona, high radon concentration differences were not observed between different rooms of the house. However, concrete walls were determined to be a source of radon. The annual radon concentration obtained indoors was 35 Bqm^{-3}, close to the Barcelona region's average value.

The radon concentration in hospital buildings built in the last 40 years in Białystok (Poland) was measured using CR-39 detectors for one year, and the highest value was obtained in the cellar of the buildings with 38.4 ± 36.7 Bqm^{-3} [219]. Measuring hospital buildings within the scope of indoor radon has raised the perspective that measurements can be made outside of houses such as school buildings. Indoor radon concentration measurements were made using LR-115-type nuclear trace detectors in Mexico, and the average radon concentration obtained was 55.6 ± 4.9 Bqm^{-3}, approximately 62% lower than the limit value [220]. In addition, a good correlation was observed between the annual average of the indoor radon concentrations and the construction materials, and concrete ceilings and concrete floors had higher radon concentration values. As a result of a study [221] in which the indoor radon levels were measured in 42 workplaces in Greece, the average radon concentration was 95 ± 51 Bqm^{-3}, well below the recommended limit values. No statistically significant seasonal change was detected in a comparison of summer and winter measurements. However, the radon concentrations measured in workplaces on the basement and ground floors were reported to be significantly higher than those measured on the first and upper floors. In Nigeria, the radon concentration was measured for three months using CR-39 detectors in secondary schools, and the average radon concentration was stated to be 45 ± 27 Bqm^{-3} [222]. However, this study reported higher radon concentrations on the ground floors than on the upper floors. Indoor radon concentration measurement throughout India was carried out using solid-state trace detectors, and the average radon concentration value obtained was in the range of 4.6 to 147.3 Bqm^{-3} [223].

As a result of a study [224] in which the main factors affecting the indoor radon concentrations in Switzerland were investigated, radon gas concentration measurements made using electret detectors were 35% higher than measurements made using trace detectors. Regarding the building characteristics, the radon concentration of apartments obtained was significantly lower than that of detached houses. Concrete-based buildings were reported to have the lowest radon concentrations. Additionally, radon concentration values were stated to decrease at higher outdoor temperatures.

Radon concentration measurements were made using CR-39 detectors for 6–7 months in 25 newly built energy-efficient houses in Romania, and the average value was 160 Bqm^{-3}, which was 27% higher than the average value reported for traditional houses in Romania [225]. In a study [226] conducted to measure the radon concentrations in public workplaces in Australia, the average radon concentration for all workplace categories was found to be 10.5 ± 11.3 Bqm^{-3}. Among workplaces, the radon concentration in basements and closed areas was found to be significantly higher than in other locations. Poor ventilation was stated as the most likely cause of increased radon levels in these places. During working hours, the radon concentrations tended to be lower than at other times of the day. This situation can be attributed to ventilation systems, including air conditioners and natural ventilation, which normally operate during working hours.

In a study [227] in which the effects of environmental factors on the indoor radon concentration levels in the basement and ground floor of a building were examined, the maximum values for the indoor radon concentration were reported to be observed in the autumn–winter season, and the minimum concentration values were observed in the spring–summer season. The monthly average indoor radon concentration value of 29 ± 21 Bqm^{-3} in the laboratory was below the recommended limit values. However, in an unventilated basement, the average monthly indoor radon concentration was very high, at 1083 ± 6 Bqm^{-3}, with little seasonal variation. The indoor temperature, indoor barometric pressure, and outdoor wind direction did not have a clearly indicated relationship with the indoor radon concentration. In the studies [226,227], which examined the effect of building floor on indoor radon levels, it was revealed that more detailed observations should be made. Singh et al. [228] conducted the measurement of indoor radon concentrations in India, and they declared that the annual average radon concentration observed in residences varied between 37 ± 18 Bqm^{-3} and 80 ± 28 Bqm^{-3}, and the radon concentration was higher in winter than in summer and spring. Similar observations were made in another study [229] conducted in India. The indoor radon concentration in 3233 houses located in a radon-prone area in France was measured as 147 Bqm^{-3}, and higher values were reported to be obtained in older houses built with granite or other stones, with flat concrete floors, and without any ventilation system [230].

In the desert climate of Jordan, the indoor radon concentration was measured using CR-39 passive trace detectors, and the average radon concentration was 29.6 Bqm^{-3}, which is below the limit value recommended by the World Health Organization (100 Bqm^{-3}) [231]. In a study [232] in which the distribution of radon concentrations was examined using passive trace detectors in childcare facilities in South Korea, the average radon concentration was 52 Bqm^{-3} according to the 5-month measurement results, with this result being approximately one-third lower than the recommended upper limit. In Saudi Arabia, the average radon concentration in old houses (20.4 Bqm^{-3}) was reported to be twice as high as in new buildings (9 Bqm^{-3}) and 25.4 Bqm^{-3} lower than the reported world average value of 40 Bqm^{-3} reported by UNSCEAR [233,234]. The indoor radon concentration in work areas was stated to be safe in terms of human health.

The indoor radon concentration was measured using solid-state nuclear signature detectors in residential buildings in India, and the average radon concentration value was 25.52 Bqm^{-3}, which was slightly higher than the nationwide average value [235]. In Hungary, the average indoor radon concentration was 108 Bqm^{-3} based on data from 415 sampling points between 1995 and 2016 [236]. Generally, higher radiation was detected in houses containing slag than in buildings without slag. Furthermore, it was concluded that the recommended minimum duration for short-term radon measurement should be at least three days, even if performed under closed conditions.

As a result of a study [237] conducted in Saudi Arabia that estimated the indoor radon concentration levels and examine the seasonal changes in these levels, it was found that in all houses, the radon concentration on the ground floor was higher than on the first and second floors, with the highest concentration results in winter (24.33 $\pm$ 11.10 Bqm^{-3}) and the lowest concentration results in summer (14.54 $\pm$ 5.50 Bqm^{-3}), indicating an obvious seasonal variation. It was emphasized that the overall measurements were obtained with an average of 19.23 $\pm$ 8.13 Bqm^{-3}, lower than the action level of 100 Bqm^{-3} recommended by WHO. It was finally stated that the present results indicated that the amount of ventilation was an important factor affecting the indoor radon concentrations. As a result of another study [238] conducted that measured the indoor radon concentrations in the western and southwestern regions of Saudi Arabia, the average radon concentration value obtained was 32 Bqm^{-3}, the value of which was below the world average (40 Bqm^{-3}; see [235]).

Tchorz-Trzeciakiewicz and Olszewski [239] determined that although the radon concentrations were over 100 Bqm^{-3} in some residences in some seasons in their study area, no residences exceeded the average indoor radon concentration of 300 Bqm^{-3} (recommended by the EU action level). However, long-term exposure to indoor radon at levels of 100 Bqm^{-3} was reported to cause a statistically significant increase in lung cancer. Seasonal changes in almost all houses were stated to occur, with the highest values in winter and the lowest values in summer. The indoor radon concentrations were stated to vary by 4 to 6 times even in houses of the same type of buildings, with the same soil types, or on the same floors. Therefore, taking annual radon concentration measurements was emphasized.

Ivanova et al. [240] analyzed the spatial distribution of the indoor radon concentration in school buildings in Bulgaria, and they found an average radon concentration of 160 $\pm$ 175 Bqm^{-3}. It was stated that the construction year of the building had the highest impact on the difference in indoor radon concentration among schools. According to the results of indoor radon measurements conducted in Cameroon, the average indoor radon concentration value exhibited a low-risk level compared to the permissible limits, with a value of 42 Bqm^{-3} [241]. The annual arithmetic average of the radon concentration in Beijing obtained was 42 $\pm$ 13.7 Bqm^{-3} [242]. It was reported that the radon concentration in residences on the ground floor was significantly higher than those on other floors. No difference in the radon level between residences on other floors was highlighted, and buildings built after 2010 had higher radon concentrations than those built in the 1980s, 1990s, and 2000s.

Al-Hubail and Al-Azmi [86] reported that the average radon concentration in secondary school buildings in Kuwait was 24.9 Bqm^{-3}, well below the action level. Akbari et al. [243] examined a detached house in Stockholm (Sweden) and emphasized that the air exchange rate, indoor temperature, and humidity had significant effects on the indoor radon concentration. It was stated that increased air exchange rate reduced the radon levels, the radon-level-minimizing temperature range was 20 to 22 °C, and the apt relative humidity was 50–60%.

Büyükuslu et al. [244] examined the campus buildings of Giresun University (Turkey) and obtained an average concentration value of 193.7 Bqm^{-3}, which was observed to be below the recommended limits. Kuluöztürk et al. [23] determined that the permissible limit value was determined to be exceeded in 10% of the examined houses in Ahlat (Bitlis, Turkey). It was also determined that the annual dose values of 78.7% of the houses exceeded the limit values. In a study [245] in which seasonal changes in the indoor radon activity concentrations were determined in 97 households in the Trabzon province (Turkey), the annual average indoor radon activity concentration varied between 8 and 583 Bqm^{-3}, and the average winter/summer radon activity concentration ratio obtained was 3.62. Alkan and Karadeniz [246] obtained an average radon concentration of 161 Bqm^{-3} in campus buildings in İzmir (Turkey). It was found that the radon concentrations in classrooms were generally higher than in offices. A difference was determined between the ground and upper floors regarding the radon concentration.

As the results of radon concentration measurements made by TAEA [247] in approximately 5500 houses in 59 cities in Turkey, the average value was 82.66 Bqm^{-3}, which is well below the limit values (<400 Bqm^{-3} for houses).

Table 6 summarizes many of the studies on the indoor radon concentration measurements (IRCMs) conducted worldwide in the last 40 years, which are considered important in presenting up-to-date results.

Table 6. IRCM results, measuring devices, measurement locations, and numbers.

City/Country Name	IRCM (Bqm^{-3})	Measuring Device	Measurement Location and Number	Ref. No
Hong Kong	45	Charcoal canisters and gamma spectrometer	Housing, 39 units	[215,216]
Podgorica, Montenegro	26.4	Passive time-integrated radon dosimeter	Housing, 110 units	[217]
Barcelona, Spain	35	LR-115 Nuc. Trace Det.	Housing, 4 units (6 rooms in each house)	[218]
Białystok, Poland	38.4 ± 36.7	CR-39 Trace Det.	Hospital, 3 units (3 different floors of each hospital)	[219]
Zacatecas, Mexico	55.6 ± 4.9	LR-115 Nuc. Trace Det.	Housing, 202 units	[220]
Greece	95 ± 51	S-type E-PERM Det.	Workplace, 42 units	[221]
Nigeria	45 ± 27	CR-39 Trace Det.	School, 35 units	[222]
Romania	160	CR-39 Trace Det.	Housing, 25 units (50 different rooms of energy-efficient buildings)	[225]
Brisbane, Australia	10.5 ± 11.3	RAD-7	Workplace, 29 units	[226]
France	147	EasyRAD passive dosimeter	Housing, 3233 units	[230]

Table 6. *Cont.*

City/Country Name	IRCM (Bqm^{-3})	Measuring Device	Measurement Location and Number	Ref. No
Jordan	29.6	CR-39 Trace Det.	Village in the desert, 13 units	[231]
South Korea	52	RSV-8 Alpha Trace Det.	Nursery, 230 units	[232]
Hungary	108	CR-39 Trace Det.	Housing, 415 units	[236]
Kuwait	24.9	Radon monitor (AlphaGUARD)	School, 46 units	[86]
Plovdiv, Bulgaria	160 ± 175	CR-39 Trace Det.	School, 16 units (331 rooms)	[240]
Cameroon	42	RADTRAK Det.	Housing, 140 units	[241]
Beijing, China	42 ± 13.7	CR-39 Trace Det.	Housing, 800 units	[242]
Saudi Arabia				
West and southwest	32	S-type E-PERM Det.	Housing, 1119 units	[238]
Dammam	20.4	RAD-7	Housing, 16 units	[233]
El-Harc	19.23 ± 8.13	RAD-7	Housing, 84 units	[237]
India				
General, across-country	4.6–147.3	Nuc. Trace Det. (SSNTD)	Housing, 1500 units	[223]
Palakkad	25.52	LR-115 Nuc. Trace Det.	Housing, 25 units	[235]
Haryana	37 ± 18–80 ± 28	LR-115 Nuc. Trace Det.	Village houses, 13 units	[228]
Turkey				
Giresun	193.7	CR-39 Trace Det.	Univ. buildings, 19 units	[244]
Bitlis/Ahlat	259.86	CR-39 Trace Det.	Housing, 50 units	[23]
Trabzon	8–583	CR-39 Trace Det.	Housing, 97 units	[245]
İzmir	161	LR-115 Nuc. Trace Det.	Univ. building, 1 unit (4 different rooms)	[246]

The indoor radon concentration readings in buildings vary from building to building as they are affected by factors such as the geological structure of the region of the building, the material type of the building, and user habits. Therefore, the values in Table 6 represent the average indoor radon concentration values. Research on radon gas measurement in concrete is in progress. Bulut and Şahin [248] conducted a study to investigate the hypothesis that radon gas might be above the standard values in self-compacting concrete (SCC), which contains more powder material than traditional concrete. The radon gas concentrations of SCCs with different mineral additives (fly ash, silica fume, and ground granulated blast furnace slag) and their ratios (5%, 12.5%, and 20%) at the end of 7, 14, 21, 28, 56, 90, and 120 days were measured using CR-39 nuclear trace detectors in closed glass environments specially produced for radon measurement purposes. The radon gas concentration values of the concrete increased with an increase in the fly ash ratio and decreased with an increase in the silica fume ratio. While the radon gas emission of concrete containing 5% blast furnace slag decreased, 12.5% and 20% increased its emissions. These results confirmed the hypotheses of the research based on the type and ratio of mineral additives.

4. Conclusions

This article reviews in detail studies on radon gas measurements in concrete and buildings. Within the scope of the study, the formation of radon, the radon concentration limits, and radon–human health, radon–concrete, and radon–building relationships were discussed comprehensively. The results obtained within the framework of this study are summarized below:

- The main source of radon, a radioactive gas that occurs spontaneously in nature, is rocks and soil derived from rocks. The risk of radon gas is especially high in areas where granitic rocks, their dykes, and volcanic rocks exist.
- The radon exhalation rate of concrete is affected by the curing time, concrete density, temperature and humidity effects, the water/cement ratio, the void structure of the concrete, its compressive strength, and the aggregate/cement/mineral additive types. Radium or radon enters concrete through components and cracks, and the pore structure allows the diffusion of radon gas. It can be said that compact concrete produced from radium-free components will exhibit a low radon potential.
- Natural, artificial, and by-product construction materials rich in uranium can create in-door radiation sources. For this reason, radioactivity analyses and dose evaluations of building materials need to be made. The use of materials containing radon above the limit values in buildings (houses, schools, hospitals, prisons, etc.) should be prevented. It is recommended to use fly ash and slag, especially in the concrete and cement industry, after radioactivity analysis.
- For indoor radon concentration measurements, the safest measurement method, the most accurate period of time, and the most suitable measurement location to use must be answered to within a global standard.
- It has been reported that radon gas, which ranks first among the natural and artificial radiation sources at 42%, causes lung cancer. Therefore, social awareness of the risks of radon gas should be created, and programs should be developed to reduce these risks.
- Attempts to develop portable devices for practical indoor radon concentration readings have begun to yield results (e.g., Morishita [249]). Researchers need to be encouraged and funded to disseminate such devices.
- More scientific studies should be conducted on the radon exhalation rate of concrete, and different parameters affecting this rate should be revealed. Although more studies have been conducted on the indoor radon concentration of concrete buildings than on the radon exhalation rate, it is thought that standardization is needed to ensure global validity on this subject.

Author Contributions: Conceptualization, H.A.B. and R.Ş.; methodology, H.A.B. and R.Ş.; validation, H.A.B. and R.Ş., investigation, H.A.B. and R.Ş.; resources, H.A.B. and R.Ş.; data curation, H.A.B. and R.Ş.; writing—original draft preparation, H.A.B. and R.Ş.; writing—review and editing, H.A.B. and R.Ş.; visualization, H.A.B. and R.Ş.; supervision, H.A.B. and R.Ş. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Atatürk University, grant number [FDK-2020-7658].

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the Atatürk University Coordinatorship of Scientific Research Projects for supporting the study.

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

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