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EXPLORING RADON: FROM SOURCES AND MIGRATION FACTORS TO HEALTH EFFECTS AND MITIGATION STRATEGIES

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ABSTRACT
Radon, a naturally occurring radioactive noble gas, is colorless, odorless, and can be found in indoor and outdoor air, water, and soil. It is responsible for approximately 50% of the annual effective dose of natural radioactivity. Numerous scientific studies have confirmed that radon is the second leading cause of lung cancer deaths, following tobacco use. While many review papers have been published on radon, there remains a gap in research regarding the comprehensive understanding of the potential health risks associated with radon exposure. This review focuses on recent advancements in the understanding of environmental health risks linked to radon, with particular emphasis on the key factors influencing radon migration and exposure. The review explores the characteristics of radon, conversion factors for radon exposure, and methods for its measurement. Additionally, it addresses the influencing factors for radon migration, such as geological and environmental variables, and discusses various instruments and techniques used for radon assessment. By synthesizing current knowledge and emphasizing the need for proactive measures, this review aims to fill the research gap in the understanding of radon-related health risks. It also highlights the urgent need for future research to better inform public health strategies and interventions aimed at mitigating radon exposure.

Keywords: Radon, Radioactivity, Environmental health risk, Radon in water, Health effect

INTRODUCTION

One of the by-products of ^{238}U decay series is radon (^{222}Rn) isotope which is created continuously from alpha decay of ^{226}Ra in soil and minerals (Rahimi et al., 2022). Radon is a radioactive element that lacks flavor, color, or smell. Radon atoms (^{222} Rn) release from soil grains happen as a result of ^{226}Ra decay. Groundwater and the empty spaces surrounding soil grains are the next places where radon gas is carried. Therefore, in the end, the amounts of radon gas in the air rise (Grzywa-Celińska et al., 2020).The three naturally occurring isotopes of radon are produced by three distinct radioactive decay processes, starting with Uranium-238 (^{238}U), Thorium-232 (^{232}Th), and Uranium-235 (^{235}U). Radon (^{222}Rn) belongs to the ^{238}U decay family and has a half-life of 3.82 days(Degu Belete & Alemu Anteneh, 2021). The gas known as radon is usually considered a health risk when evaluating risk factors from exposure to it. After radon gas is inhaled or consumed, radon daughters (polonium-218 and polonium-214), which are alpha particles and account for about 90% of the total radiation dosage from radon exposure, are produced (Farai et al., 2023). Radon comes in different isotopes such as radon-219, radon-220 and radon-222. Radon-222, often simply referred to as radon and is the most common and extensively researched isotope. The radioactivity of radon-222 stems from its decay process, in which it undergoes a series of transformations, each resulting in a distinct decay product. Throughout this process, radon-222 emits alpha particles, beta particles, and gamma radiation (Abed et al., 2024).

Ionizing radiation, particularly alpha particles, can lead to DNA damage through chromosomal aberrations, double-strand DNA breaks, and the production of reactive oxygen species (ROS). This damage can result in shortened cell cycles, apoptosis, and an increased risk of carcinogenesis (Borrego-Soto et al., 2015).

These particles and radiation are worrisome since they can ionize atoms and molecules, alpha particles can induce chemical changes that may result in DNA damage within biological systems. Specifically, alpha particles are intensely ionizing and can pose significant health dangers if inhaled or swallowed (Robertson et al., 2013). The risk depends on factors such as the concentration of radon gas, the duration of exposure, and the type of enclosed setting. Radon levels tend to be higher in buildings located in areas with uranium-rich soil and rock. Additionally, poorly ventilated spaces, like basements and crawl spaces, can accumulate higher concentrations of radon. Long-term exposure to elevated radon levels significantly increases the risk of lung cancer, especially for smokers or those with prolonged exposure. Therefore, radon is a health risk primarily when concentrations are high in poorly ventilated, enclosed environments, and individuals are exposed for extended periods. Radon gas is particularly significant in indoor environments due to its capability health hazards at high concentrations. As a widespread environmental pollutant, radon exists at varying levels around the world. Its presence indoors is especially concerning because people often spend a considerable amount of time inside their homes or workplaces (Mphaga, Utembe, et al., 2024). The main issue with radon is its link to lung cancer, where it ranks as the most cause of lung cancer after smoking. Inhaling radon and it is decay products usually caused damaging of DNA and increasing the risk of cancer (Dobrzyńska et al., 2023). The risk becomes especially severe when radon concentrations are elevated and exposure is sustained over time (Ngoc et al., 2023). As a result, radon can infiltrate dwellings, particularly those with inadequate airflow, and build up to dangerous levels. Although radon is a health risk in any enclosed setting, it is especially concerning in buildings where individuals spend a considerable amount of time (Kubiak & Basińska, 2023). The threat posed by high concentrations of radon and its potential contribution to the development of numerous lung cancers is considerable and cannot be exaggerated. Due to the rising public concern about cancer in recent years, research on radon has become increasingly important (Riudavets et al., 2022).

Water quality plays a crucial role in public health. The World Health Organization reports that 75% of diseases in developing countries are caused by consuming contaminated water. Additionally, approximately 884 million people worldwide rely on unsafe drinking water (Lin et al., 2022). Water covers approximately 75% of the Earth's surface, making it the most abundant substance. However, in many developing countries, such as Nigeria, access to clean water and proper sanitation services is often inadequate (Isukuru et al., 2024). Consequently, a significant portion of the urban population depends on groundwater aquifers by using "hand dug wells" (HDW) to obtain water for drinking and domestic purposes, including cooking, washing, and bathing (Grönwall & Danert, 2020). According to (Balasooriya et al., 2023) in low-income, high-density residential areas of cities in developing countries, hand dug wells are particularly vulnerable to various sources of pollution. This underscores the necessity of evaluating the water quality from these wells to ensure they are safe for drinking (Balasooriya et al., 2023). The primary water sources for drinking are surface and subsurface water (borehole and well water). Radionuclide concentrations in underground water are often higher than in surface water. This results from radioactive materials dissolving as they travel through rocks and soil (Oyebanjo & Magbagbeola, 2015). Since it's not possible to eliminate the source of radon, mitigation methods focus on lowering radon levels as much as possible and ensuring that the solutions remain effective over time (Khan et al., 2019). Typically, the selection of the most appropriate radon mitigation method depends on regarding the initial radon levels and the type of flooring used. Generally, mitigation strategies either aim to dilute or redirect radon away from its source or enhance airflow within the enclosed environment (EPA, 2016). In current dwellings, homeowners are advised to establish radon reduction strategies if radon levels exceed the action level of 200 Bq/m^3. For new homes constructed in radon-affected regions since 1993, radon management is regulated by specific building codes and updates (MHCLG 2013) as well as guidance [BR211](IAEA, 2015). The building regulations and BR211 guidance suggest employing radon prevention methods, which may include basic or full radon protection, based on the radon potential of the area (Lyons et al., 2023).

This review provides a comprehensive analysis of radon, addressing gaps in understanding its sources, characteristics, and the factors influencing indoor concentrations. It explores the role of geological conditions, atmospheric variables, and building designs in radon migration, alongside an evaluation of current detection methods and technological advancements in monitoring. The review highlights the health risks of radon exposure, particularly its established link to lung cancer, and discusses the biological mechanisms behind cellular damage. It also examines various mitigation strategies for reducing radon levels in residential and occupational settings, aiming to identify effective approaches for public health and policy. By synthesizing this information, the review seeks to guide safer living and working environments, contributing to better radon risk management. Despite previous reviews, critical issues, such as environmental impacts and long-term health hazards, remain underexplored, making this analysis essential for advancing knowledge and addressing these concerns effectively.

Radon

The primary natural source of radiation is radon that is responsible for approximately 21,000 lung cancer deaths in the U. S. A each year. (Grzywa-Celińska et al., 2020). Radon (Rn) is a radioactive gas that forms naturally from the decay of uranium, thorium, or radium that are found in soil, rock and groundwater. Radon have three major isotopes which include (^{222}Rn), thoron (^{220}Rn) and actinium (^{219}Rn) with half-lives of 3.8 days, 55.8 seconds and 3.98 seconds respectively (Degu Belete & Alemu Anteneh, 2021). These isotopes are produced when ^{232}Th, or ^{234}U and ^{238}U, which are found in soil, rocks, and air, spontaneously decays. ^{222}Rn is a component of the ^{238}U decay series, whereas is a consequence of ^{222}Rn's alpha decay in the decay series of ^{232}Th (Bashir et al., 2023). The reason ^{222}Rn is significant is that, its weight is far more abundant than the total amount of all radon isotopes combined; for this reason, ^{222}Rn is the only substance that is referred to as "radon." (Vogiannis & Nikolopoulos, 2015). Radon-222 (^{222}Rn) is found in soil, rocks, water, and air due to its volatile nature. It decays into four radioactive byproducts known as progeny: polonium-218 (^{218}Po), bismuth-214 (^{214}Bi), lead-214 (^{214}Pb), and polonium-214 (^{214}Po)(Degu Belete & Alemu Anteneh, 2021). Approximately 85% of the damage caused by radon exposure is caused by the alpha-emitting radon progeny ^{218}Po and ^{214}Pb (Sakoda et al., 2021).

Rn-222 gas is found in both indoor and outdoor air since it originates from the Earth's crust and can travel by convection and diffusion to reach the atmosphere (Benà et al., 2024a). Building materials serve as the main source of indoor exposure to radon-220 (Rn-220), which has a shorter half-life of 56 seconds compared to radon-222 (Rn-222) and can only travel limited distances from its source. In a similar vein, radon-219 (Rn-219) possesses an even shorter half-life of 4 seconds, restricting its ability to flee from its origin. Consequently, exposure to Rn-219 and its decay products in the workplace is generally minimal and regarded as insignificant. Thus, ^{222} Rn and ^{220}Rn are the primary radon isotopes of concern in radiation safety. In recent years, it has become clear that exposure to these isotopes constitutes the primary source of natural radiation exposure for humans (Wang et al., 2021).

Radium serves as the precursor to radon in the uranium decay chain. Figure 1 depicts the decay chain of uranium-238, which is the most prevalent isotope of uranium. This illustration emphasizes the intermediate formation of radon during the decay process (Bulut & Şahin, 2024).

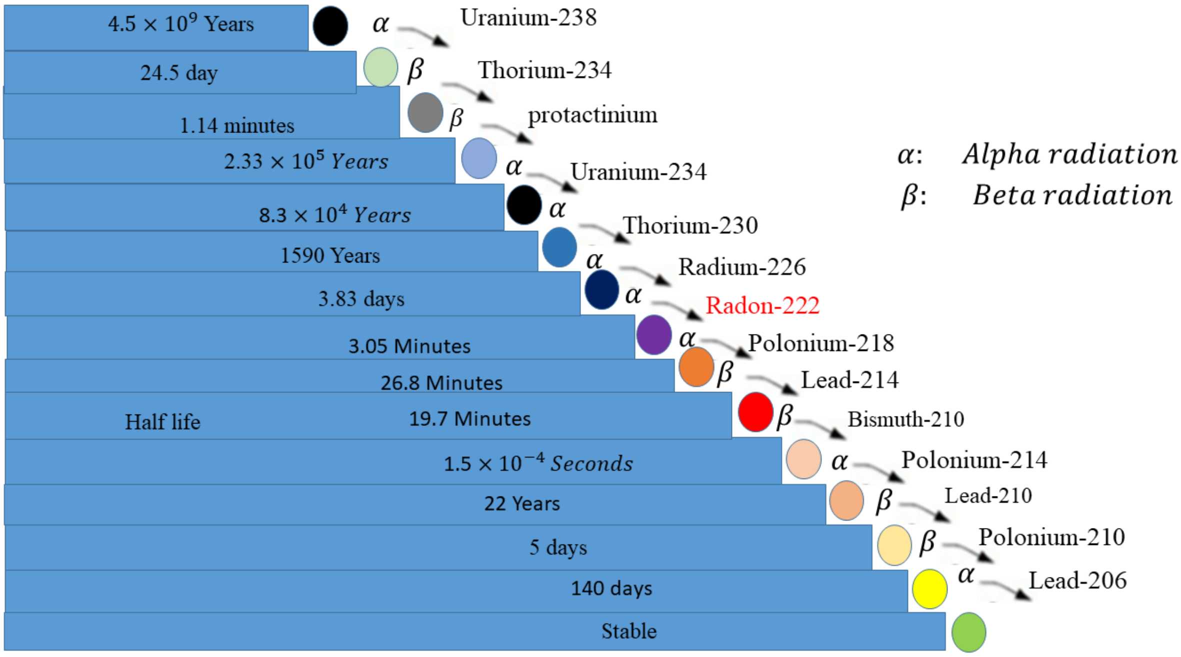

Figure 1: Uranium 238 decay chain (Bulut & Şahin, 2024)

Table 1: Characteristic of radon

S/N	Chemical Symbol	Rn
	Atomic Number	86
	Atomic mass	**222**
	Freezing point	−71.0 °C (202.15 °K, −95.8 °F)
	Vaporization point	**−61.8 °C (211.35 °K, −79.24 °F)**
	Count of protons and electrons	86
	Count of neutrons	**136**
	Category	8A group (Noble
	Crystal structure	**Cubic**
	Density	9,73g/cm^3
	Half life	**3.82 days**

After the discovery of radon (^{222}Rn) gas, which has an extremely short half-life of 3.82 days and is primarily composed of the ^{226}Ra isotope, research on the radioactivity of this gas started to gain interest (Degu Belete & Alemu Anteneh, 2021).

Sources of Radon Gas

Radon gas is a naturally occurring radioactive gas that is present in indoor environments. It originates from numerous elements found in the Earth's crust. Although rock and soil are usually thought to be the main producers of radon, other natural materials also contribute significantly to its emission (Abed et al., 2024).

Radon in the Ground and Geological Materials

Radon levels are directly correlated with uranium levels. Radon concentration varies as a result of variations in uranium concentration in the soil (Regenauer et al., 2022). The environment is exposed to radon gas in direct proportion to the local geological structure. It can build up in structures and be present in varying concentrations in rocks and soil (Benà et al., 2024a). The soil and rock formations on the property where these structures are situated are some of the sources through which radon gas can infiltrate buildings. Radon gas often seeps through existing cracks and escapes into the environment from soils and rocks that are rich in uranium, thorium, and radium, which contribute to the production of radon (Maestre & Iribarren, 2018).

The exposure to uranium in various types of bedrock is depicted in Figure 2 (M & R, 2018). The direct influence of uranium exposure on the generation of radon gas in various types of bedrock is also compared in Figure 2, where it is shown that uranium concentrations are low in basalt and sandstone-based bedrock, moderate in carbonate-based (limestone) bedrock, and rich in uranium in granite and clay-based bedrock.

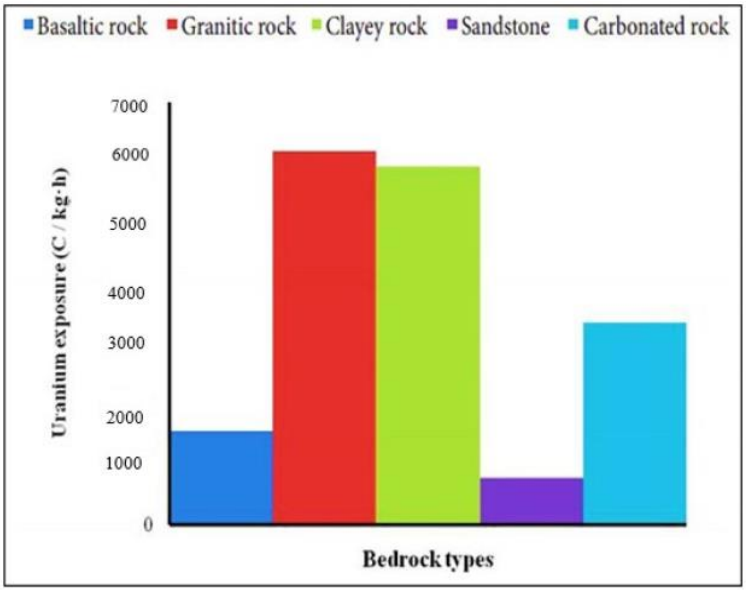

Figure 2: Uranium levels in various types of bedrock (M & R, 2018)

Hungary recorded its highest radon concentration, with an annual mean of 227 ± 10 Bq/L, gneiss, a type of rock that results from the metamorphosis of older granitic formations, has been analyzed for its radon gas levels. A study conducted in Portugal revealed that granite rocks exhibited the highest concentrations of radon gas, with values ranging from 2 to 73 Bq kg^{-1} (Freiler et al., 2016). It has been observed that uranium is more commonly found in crystalline rock types, such as granite especially in relation to igneous rocks. Due to the granitic composition of the subsurface layer, Galicia, an autonomous community in the northwest of Spain, has been recognized for having the highest indoor radon levels in the nation (Freiler et al., 2016). The emission of radon gas is affected by several factors, including temperature, uranium concentration, soil permeability, humidity levels, and the size of soil pores(Nunes et al., 2023). For instance, in extremely permeable soils, radon gas can readily rise to the surface. Active tectonic faults were highlighted as the primary geological source of enhanced radon gas emissions because of their high soil and rock permeability (Benà et al., 2022).

The below table provides the radon (Rn) concentrations in groundwater across different locations, with values expressed in Becquerels per liter (Bq/L). It includes a variety of water sources, such as boreholes, wells, hand-dug wells, and tap water, from regions in Nigeria and other countries like Saudi Arabia and Bangladesh. The table also references relevant studies that report these measurements, offering insight into the variability of radon concentrations in drinking water. This data can be valuable for understanding potential health risks associated with radon exposure in different geographical areas.

Table 2: Radon Concentrations in Groundwater Samples from Various Locations

S/N	Location	Rn Conc. (Bq/L)	Sample type	Reference
1	Katagum, Bauchi State	39.55	Borehole and well	(Abdulrasheed et al., 2024)
2	Dutse, Jigawa State	82.43	Borehole and hand dugwell	(Dankawu et al., 2022)
3	Jazan, Saudi Arabia	1.45	Well and tap	(El-Araby et al., 2019)
4	Lapai, North central, Nigeria	1.48	Hand dug well and borehole	(Umar et al., 2024)
5	Abekuta, Nigeria	14.25	Borehole and hand dug well	(Farai et al., 2023)
6	Kiyawa, Jigawa State	36.46	Well and borehole	(Shuaibu et al., 2024)
7	Keana Nasarawa, Nigeria	2.25	Well and borehole	(Bako et al., 2023)
8	Bosso, Minna North central, Nigeria	6.93	Well and borehole	(Kolo et al., 2023)
9	Gadau, Bauchi state	38.3	Well	(Shu'aibu et al., 2021)
10	Ota, Ogun state	7.7	Well	(Jidele et al., 2021)
11	Dhaka city, Bangladesh	7.13	Pump water	(Pervin et al., 2020)
12	Ogbomosho, Nigeria	1.86	Well and borehole	(Abiodun & Aanuoluwa, 2019)
13	Bagwai and Shanono. Kano state	20.13	Borehole and hand dug well	(Hannafi et al., 2024)
14	Southwestern, Nigeria	56.8	Well and borehole	(Oni et al., 2014)
15	Sabon Gari, Kaduna state	14.9	Well and borehole	(Syahnita, 2021)
16	Damaturu, Yobe	2.75	Sachet water	(Abba & Umaru, 2020)
17	Agbhabu, Ondo state	18.45	Wellwater	(Faweya et al., 2021)

Annual Effective Dose (AED) Values for Radionuclides in Groundwater Samples from Various Locations

The table below presents the Annual Effective Dose (AED) values for radionuclides in groundwater samples across different locations. The AED values are categorized by different ingestion scenarios: ingestion through water (AEDing(A)), ingestion via food (AEDing(C)), and ingestion from inhalation (AEDing(I)), expressed in millisieverts (mSv). The table includes data from diverse regions in Nigeria, Saudi Arabia, and Bangladesh, offering insight into the potential radiation exposure from drinking water in these areas. Some data points are missing or incomplete, highlighting the need for further research. These AED values are crucial for evaluating the potential health risks associated with radionuclide exposure in drinking water

Table 3: Annual Effective Dose (AED) values for radionuclides in groundwater samples across different locations

S/N	Location	AEDinh	AEDing(A)	AEDing(C)	AEDing(I)	Reference
1	Katagum, Bauchi State	0.1	0.29	0.43	0.51	(Abdulrasheed et al., 2024)
2	Sabon Gari, Kaduna state	0.4	0.01	0.02	0.03	(Syahnita, 2021)
3	Dutse, Jigawa State	0.22	…………	………….	………	(Dankawu et al., 2022)
4	Jazan, Saudi Arabia	0.002	0.002	0.001	0.03	(El-Araby et al., 2019)
5	Lapai, North central, Nigeria	0.007	0.007	0.006	0.02	(Umar et al., 2024)
6	Kiyawa, Jigawa State	0.09	0.27	0.47	0.40	(Shuaibu et al., 2024)
7	Keana Nasarawa, Nigeria	………..	0.02	0.03	………..	(Bako et al., 2023)
8	Bosso, Minna North central, Nigeria	………..	0.09	0.09	0.06	(Kolo et al., 2023)
9	Ota, Ogun state	0.39	………..	…………	………..	(Jidele et al., 2021)
10	Dhaka city, Bangladesh	0.05	………..	………..	………..	(Pervin et al., 2020)
11	Bagwai and Shanono. Kano state	……….	0.20	0.28	0.30	(Hannafi et al., 2024)
12	Ogbomosho, Nigeria	0.02	………..	…………	…….	(Abiodun & Aanuoluwa, 2019
13	Damaturu, Yobe state	……….	0.09	0.17	………..	(Abba & Umaru, 2020)
14	Agbhabu, Ondo state	………..	0.08	0.08	0.09	Faweya et al., 2021)

Radon from Water

Groundwater originates from geological formations known as aquifers, and it can have elevated radon concentrations due to its interaction with radium-rich soils and rocks. In many countries, drinking water is sourced from various water supplies, including groundwater accessed through wells and boreholes(Shah et al., 2024). However, because it is discharged into the atmosphere as opposed to groundwater, which contains granite, sand, and sediments, the concentration of radon in surface water is often lower (Nam et al., 2024) . As water temperature rises, so does the quantity of radon gas released into the atmosphere. the health risks linked to elevated radon levels in drinking water mainly stem from inhaling radon present in indoor air and tap water, while direct ingestion plays a lesser role (Manawi et al., 2024).

Groundwater may include dissolved radon, which could be emitted into enclosed air when water is utilized for household activities, especially in places with high radium concentrations. Analogously, uranium and thorium residues can be present in some building materials, such granite and concrete, which can cause radon to escape into enclosed areas (Abed et al., 2024). The primary source of radon is the ground, where it originates from rocks, soil, and construction materials like concrete, cement, and paint. Radon infiltrates buildings through floors, openings and cracks in the walls. (Esan, Sridhar, et al., 2020). Due to its solubility in water, it can also permeate from rocks in the Earth's crust into water and exist in different amounts in water sources including surface and groundwater. The amount of radon present in water depends on the temperature of the groundwater, depth, location, season, and kind of rock (Purnama et al., 2021). The United States Environmental Protection Agency (USEPA) established a maximum contaminant level (MCL) of 11.1 BqL^{-1} for radon-222 in drinking water in 1999. In contrast, the World Health Organization (WHO) set a higher limit of 100 BqL^{-1} for the same substance in 2003. (Teresa & Camelo, 2022). There is a dearth of information on radon concentration and associated hazards in Nigeria, as well as a low level of public awareness of the gas (Esan, Obed, et al., 2020). More databases on the amount of radon in water sources, such as taps, wells, and boreholes, as well as the risks associated with consuming water that may contain high levels of radon, are therefore essential (Bashir et al., 2023). The radioactive decay of uranium and thorium is the first step in the process. These substances break down into radium, which subsequently changes into radon gas. This radioactive gas can seep into homes through multiple openings and migrate through the surrounding rock and soil. The ability of radon to enter indoor spaces is mostly influenced by environmental and geological variables (US EPA, 2014).

These are some important things to remember about natural radon sources.(Nna et al., 2024), (Nunes et al., 2023),(Abodunrin, 2020).

Geological Structure: The geological composition of an area significantly influences the radon concentrations found within homes. Specific rock and soil types, especially those abundant in uranium and thorium, tend to exhibit higher levels of radon. For example, formations such as shale and granite are recognized for their tendency to emit increased quantities of radon gas into the environment.

Soil Permeability: Another key factor to consider is the permeability of the soil. Radon has the ability to permeate loose or sandy soils with ease, often infiltrating homes through cracks or openings in the foundation. On the other hand, soils that are high in clay content can act as a barrier, hindering the movement of radon and leading to reduced levels of this gas indoors.

Subsurface water conditions: Radon levels in homes can also be affected by groundwater. In areas with high groundwater tables, the emission of radon gas from water into indoor air can contribute to higher levels of radon infiltration within a home. Additionally, radon may be found in well water, particularly when it is used for residential purposes.

Seasonal Variations: During the colder seasons, homes are often sealed more tightly, which can result in a higher accumulation of radon gas indoors. On the other hand, in warmer weather, improved airflow can help decrease the concentration of radon. To evaluate the potential risks and take the necessary steps to reduce radon levels indoors, it's important to understand the natural sources of radon, such as soil, rock, water, and construction materials. The first step in determining if radon levels are high in a given area is to conduct a radon test (Grzywa-Celińska et al., 2020).

Radon from Building materials

Construction materials, whether sourced naturally, artificially manufactured, or as by-products, contain different amounts of naturally occurring radionuclides from the decay chains of uranium-238 (^{238}U) and thorium-232 (^{232}Th). The gamma rays emitted by these radionuclides signify external radiation exposure, originating from external sources. In contrast, individuals within buildings are subjected to internal radiation from indoor sources, primarily from alpha particles emitted by radon and its decay products. These alpha particles can be inhaled and enter the body when radon is present in the indoor air (Szabó et al., 2013). Apart from the characteristics of the soil beneath structures, building materials and construction techniques play a significant role, particularly when it comes to indoor radon levels (Baltrocchi et al., 2024). The ability of building materials to permit radon passage is now viewed as an essential element in evaluating radon concentrations within a building. This highlights how radon gas can become trapped indoors after it infiltrates through cracks in the foundation and floors (Bulut & Şahin, 2024).The amount of radon gas released by building materials is influenced by a number of variables, including the $^{238}U/^{226}Ra$ composition, ventilation rate, and meteorological and climatic parameters (Belete & Shiferaw, 2022). It is indicates that the amount of radon that is present indoors or within buildings due to construction materials is 10 Bqm^{-3} (Kumar et al., 2017). Given that the global radon concentration on an annual average is about 40 Bqm^{-3} (Sandoval et al., 2021), construction materials contributed about 25% of the radon that was found indoors or within buildings to Turkish Atomic Energy Authority (SO, 2022) .This contribution is predicted to be 10–20 Bqm^{-3} in nations that makes up the European Union (Thumvijit et al., 2020). The Turkish Atomic Energy Authority has identified several materials known to release radon gas, including aluminous shale, granitic rocks, porphyry, tuff, pozzolana, lava, fly ash, phospho-gypsum, and various slags from aluminum, tin, and copper production. These materials are recognized for their potential to contribute to radon emissions in buildings (Verdolotti et al., 2008). Research has also explored the radon gas composition and emissions linked to commonly used building materials, including concrete, cement, brick, and aggregates (Abd-Elghany et al., 2023).

Particularly when it comes to building materials, radon can enter indoor spaces. This is a radon `exposure factor that is frequently disregarded. Naturally occurring radioactive elements that decay and release radon gas can be found in building materials. Concrete, brick and other types of stone are common building materials that can have ingredients that produce radon (Belete & Shiferaw, 2022)

Concrete: Concrete is a widely utilized construction material that can contain small quantities of naturally occurring radioactive elements. Over time, these elements may generate radon gas. The likelihood of radon emissions from concrete is influenced by several factors, such as the particular composition of the concrete mixture and the conditions under which it cures. Related What are the health risks associated with radon exposure in buildings How can homeowners test for radon in their homes What are the best practices for reducing radon levels in buildings How does the composition of concrete affect radon emissions Are there any regulations in Turkey regarding radon levels in buildings

Brick: Certain varieties of brick, particularly those with high clay materials, may naturally contain radioactive materials. These bricks may eventually leak radon gas, which would raise the radon levels within.

Stone: Certain types of stone used in construction can also contain substances that produce radon. The amount of radon emitted by a particular stone can differ based on its type and geological background. While artificial sources can contribute to higher indoor radon levels, their influence is typically less pronounced compared to natural sources. Additionally, the impact of building materials on indoor radon concentrations can vary significantly, depending on factors such as the material's radon content and the overall ventilation of the dwelling (Abed et al., 2024). Rich uranium-containing building materials are thought to be possible sources of radon gas emissions. Furthermore, variables influencing the radon gas level include the building's height, the permeability of the earth, and the quantity of radium present in the materials (Cinelli et al., 2019). Prolonged exposure to elevated levels of radon gas in confined environments, such as residences and workplaces, has been associated with a heightened risk of health problems, especially lung cancer. Thus, it is crucial to take steps to lower radon concentrations to safe levels (Ngoc et al., 2023).

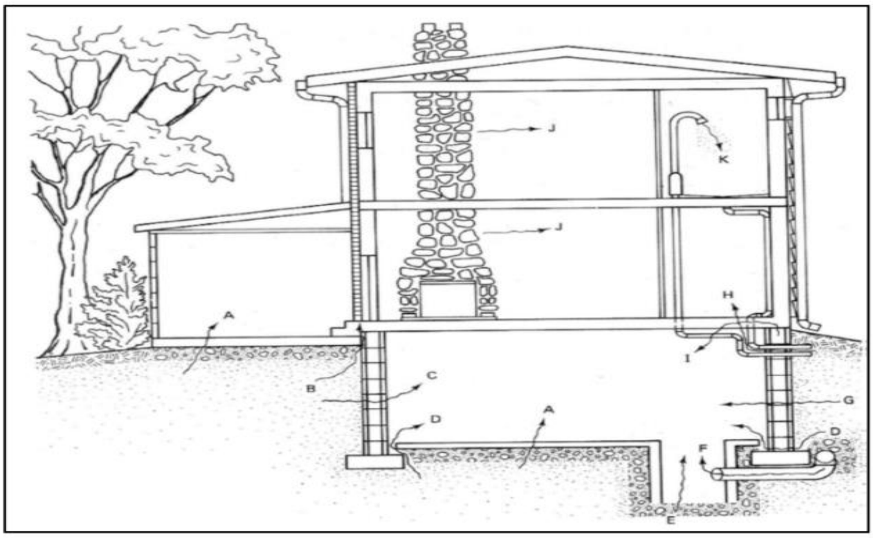

Figure 3: Methods in which radon gas enters buildings (Baltrocchi et al., 2024)

The ways that radon gas enters structures; gaps in concrete slabs, the areas behind walls covered in brick veneer that are supported by hollow block foundations , the fissures and pores in blocks of concrete, floor-wall joints, weeping (drain) tile, when directed to an open sump with exposed earth, can lead to water infiltration through various points, such as mortar joints, fissures at intersections and corners of concrete blocks and pipes, as well as through construction materials like specific types of pebbles and well water (Vogiannis & Nikolopoulos, 2015)

As can be seen in Figure 3, wall fractures, connecting points in the structure, and holes in the ground are the main ways that radon gas enters and builds up in structures. While radon is a naturally occurring radioactive gas, it should be highlighted that elevated radon levels in residential structures are not a result of natural processes but rather an unfavorable outcome of subpar building materials, ventilation, and design. One of the main factors contributing to indoor air pollution is thought to be radon (Banks et al., 2019). The need for certificates attesting to safe radon levels in buildings is growing these days (Deiana et al., 2021).

Radon Measurement Units and Conversion Factors

The standard unit for quantifying the activity of a radioactive material is the becquerel (Bq), which is defined as one radioactive decay occurring per second (Juan Carlos Lentijo, 2006). In indoor environments, the radioactive balance between radon gas and its short-lived decay products is influenced by various factors. These include the concentration and size distribution of aerosols, the room's surface-to-volume ratio, and the rate of air exchange (Vaupotič, 2024). The level of equilibrium is commonly represented by the equilibrium factor (F factor), with a value of 1 signifying total radioactive balance between radon and its short-lived airborne decay products (Makumbi et al., 2024). The F factor plays a vital role in calculating the lung dose associated with radon decay products. Research from multiple countries shows that F factors in residential settings generally range from 0.2 to 0.8 (Shahrokhi & kovács, 2023). The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the International Commission on Radiological Protection (ICRP) have established a standard global equilibrium factor of 0.4 for indoor air. In comparison, the equilibrium factor for outdoor air is usually elevated, commonly falling between 0.6 and 0.8 (K. W. Kang, 2016). Given these factors, various methods are employed to characterize airborne radon decay products. One widely used method is the equilibrium equivalent radon concentration. This measure represents the radon activity concentration (in Bq/m^3) that would be in equilibrium with its short-lived decay products, providing the same potential alpha energy concentration as the actual non-equilibrium mixture present in the air being analyzed (Leuchner et al., 2019). The potential alpha energy concentration refers to the total potential alpha energy per unit volume contributed by the short-lived radon decay products in the decay chain up to ^{210}Pb (with a half-life of 22.3 years). Its SI unit is joules per cubic meter (J/m^3) (Feng et al., 2019) Traditionally, the potential alpha energy exposure of workers was quantified in working level months (WLM). One working level (WL) is defined as a combination of short-lived radon decay products that generates 1.3×10^5 MeV of potential alpha energy. This energy is approximately equivalent to that produced by radon progeny in equilibrium with 3.7 Bq of radon. The WLM unit was developed to evaluate occupational exposure, representing one WL sustained over a work month of 170 hours. (Vargas et al., 2020).

Influencing factors of radon migration

A thorough exploration of influencing factors is crucial for understanding how radon moves through the environment and accumulates indoors. Below is a detailed explanation of the primary factors influencing radon migration (Jin et al., 2020).

Soil and rocks factors

Porosity of soil and rocks

Porosity describes the ability of soils and rocks to allow the passage of water and gases. Materials with greater porosity, like sandstones and limestones, have larger pores and fractures, which enhance the movement of radon through these substances (Rasheed et al., 2022). On the other hand, soils and rocks with low porosity, like clays and shales, are more likely to retain radon and restrict its movement. The porosity of these materials is crucial in determining how radon migrates through the environment, significantly influencing indoor radon levels (Benà et al., 2024b). In regions with elevated porosity, radon can readily move through the soil and infiltrate buildings, thereby raising the risk of exposure. Conversely, in regions with low porosity, radon is more likely to be trapped within the soil and may not infiltrate indoor spaces, thereby reducing the risk of exposure. (Esan, Obed, et al., 2020). The porosity of soil and rocks is a crucial factor in identifying high-risk areas. Consequently, assessing radon concentration and exposure risk in a region involves combining measurements of soil permeability with the concentration of uranium and thorium in rocks and soils (Abed et al., 2024). For instance, granitic rocks may have low porosity but can show high permeability if they are heavily fractured. Conversely, volcanic rocks, while often possessing high porosity due to vesicles, typically have limited permeability because these pores are often poorly connected (Pereira et al., 2024). Clays, siltstones, and mudstones are characterized by low porosity, which results from their small pore sizes and limited connectivity between pores. Conversely, limestones display a wide spectrum of porosity levels, ranging from extremely low in microcrystalline varieties to significantly high in fractured limestones or those with substantial intergranular porosity (Lacey & Bissada, n.d.). The porosity of these materials is essential as it affects the ease with which radon can travel and disperse through the rock or soil. Rocks or soils that are highly permeable provide more accessible routes for radon to escape, thereby enhancing its diffusion (Othman et al., 2021). The porosity of permeable materials is influenced not only by their total porosity but also by the configuration and shape of their pores, along with the presence of clay particles. Notably, it is the effective porosity, which consists of interlinked open pores, that affects permeability, facilitating the movement of water (Bohnsack et al., 2020).

Diffusion

Diffusion refers to the movement of radon gas from areas of higher concentration, such as within soil or rock pores, to areas of lower concentration, typically in the surrounding air. This process is driven by the random motion of gas molecules and occurs as radon escapes through interconnected pore spaces and fractures in the material (Spasić & Gulan, 2022). The diffusion rate is influenced by various factors, including pore size and pressure differences across the pores. As radon moves through rocks, it can become trapped in soil, water, or structures, which may result in dangerous accumulations (Nguyen et al., 2020). Radon diffusion is also affected by factors such as temperature and the moisture level within the rocks. Generally, elevated temperatures and higher moisture levels can facilitate radon diffusion, while cooler temperatures and drier conditions are likely to slow down its diffusion rate (Copper et al., 2004). Radon can be present in pore air, dissolved in pore water, or adsorbed onto soil particles within soil pores (Beltrán-Torres et al., 2023). Soil serves as the main source of radon in the majority of buildings. The research also indicated that the migration of soil gas through openings in the building's foundation plays a crucial role in radon transport. This movement is affected by weather conditions and the operation of HVAC systems (Abodunrin, 2020).

Pressure

Pressure fluctuations in soil and rocks can impact the movement of radon as well. Generally, radon tends to flow from regions of higher pressure to those of lower pressure. (Othman et al., 2021). For instance, when the gas pressure beneath the surface surpasses atmospheric pressure, radon is driven upward toward the surface. Additionally, natural geological formations like faults, fractures, and openings in rocks can generate pressure differences, leading to zones of high or low pressure that influence radon movement (Pulinets et al., 2024). The migration of radon through these pathways can be affected by factors such as soil moisture, temperature, and the levels of other gases present in the subsurface. These conditions can either facilitate or hinder the movement of radon (Nurohman et al., 2024). The movement of radon through soil and rock is often intricate and challenging to forecast, underscoring the importance of employing multiple methods to evaluate radon levels and its migration in various geological settings(Aghdam et al., 2021). Pinault and Baubron (1997) carried out a comprehensive study on these interactions, employing signal processing methods to examine daily and semi-daily fluctuations in atmospheric pressure along with radon levels in soil gases (Arvela et al., 2016). These fluctuations in pressure enabled the researchers to determine three essential parameters related to soil gas transport: tortuosity, which reflects the intricacy of the gas flow pathway; the ratio of intrinsic permeability to effective porosity (the fraction of porosity that permits gas movement); and the pressure gradient (Sun et al., 2022). This accurate evaluation of transport parameters is facilitated by a comprehensive and representative approach that offers significant insights into the depth of radon sources and the duration it takes for radon to ascend to the surface during emissions from deeper strata (Bashir et al., 2023).

Additional component

Component such as the existence of groundwater, weather conditions, and the landscape can also affect the movement of radon (Manawi et al., 2024)

Underground water

Elements like groundwater presence, climatic factors, and terrain features can also impact the transport of radon (Olise et al., 2016). This occurs because water molecules tend to adhere to soil particles, forming a layer that restricts the space available for gas movement (Rhodes, 2014). Nevertheless, when water flows through soil or rock, it can carry dissolved radon to different locations. Radon that dissolves in groundwater can be transported with the moving water, potentially dispersing the gas to new areas and heightening the risk of human exposure (Moreno et al., 2018). Radon levels in groundwater can vary considerably based on the surrounding geology and various environmental conditions. Therefore, it is crucial to regularly monitor radon concentrations in both groundwater and indoor air to evaluate potential health risks to individuals (Samaila, 2023). Moreover, water can lead to increased radon levels indoors, as activities that involve water sources, such as using showers and faucets, can emit radon gas into the atmosphere (Vinson et al., 2008). A recent investigation by Ibánhez et al. (2023) conducted a thorough survey of the Ría de Vigo catchment, recognized as the most radon-sensitive region on the Iberian Peninsula (Ibánhez et al., 2023). The researchers aimed to determine the environmental factors that lead to human exposure to radon during household water usage. Their results indicated that continental waters in the area were notably enriched with radon, with groundwater exhibiting radon concentrations one to two orders of magnitude greater than those present in rivers (Nagaraja et al., 2019) This occurrence was linked to seasonal changes in water consumption, recharge cycles, and thermal convection. The authors caution that elevated radon levels indicate that utilizing untreated groundwater in households can lead to a cumulative effective radiation dose surpassing the recommended threshold of 0.1 mSv/y. They advise the installation of radon remediation and mitigation systems prior to using untreated groundwater for residential purposes, particularly during the dry season. This is crucial since more than 70% of the radiation dose is attributed to radon emissions from indoor water and subsequent inhalation (*(United States Environmental Protection Agency, 2012) 1*, 2014).

Climatic component

Climatic component such as temperature, humidity, and precipitation play a significant role in the movement and distribution of radon (Rey et al., 2023). Variations in temperature can affect soil pressure, subsequently influencing the transport of radon (Cinelli et al., 2019). Additionally, lower temperatures often lead to increased condensation, which can hinder radon's diffusion. Soil moisture also impacts radon's permeability and diffusion capacity (Density et al., 2020). Saturated soil can hinder the movement of radon by serving as a barrier to gas diffusion. During periods of heavy precipitation, the soil becomes saturated, which complicates radon diffusion and raises the likelihood of radon being transported by groundwater (Jin et al., 2020). In contrast, radon diffusion tends to be more effective in drier climates due to reduced soil moisture. A research study by Sundal et al. (2008) explored the impact of various meteorological factors on soil radon levels within permeable glacial sediments in Kinsarvik, Norway, emphasizing the significant role that climatic and meteorological conditions play in this process (Gil-Oncina et al., 2022).

The authors carried out continuous monitoring of soil radon concentrations for ten months, measuring factors such as temperature, precipitation, wind speed and direction, air pressure, and soil moisture content. Their findings indicated that variations in air temperature significantly affected soil radon levels on both a seasonal and diurnal basis. The study found that variations in temperature between soil air and atmospheric air led to air movement at different elevations within the ice-marginal deposit. Significantly, changes in air flow direction were observed as ambient temperatures neared the annual average. The main influence on soil radon concentrations was air pressure, whereas factors such as precipitation, wind speed and direction, and soil moisture seemed to have minimal or no effect (Nunes et al., 2023).

Topography

Topography plays a significant role in radon transport. Features such as slopes, hills, and depressions can modify air circulation and soil pressure, which in turn influences the movement of radon (Report, 2023). In rugged terrain, enhanced groundwater drainage and air circulation can lead to lower radon accumulation (Sukanya et al., 2021). Conversely, depressions and low-lying areas can trap radon, resulting in higher gas concentrations (Shah et al., 2024). The impact of atmospheric conditions and topography on radon levels is emphasized by (Rey et al., 2023). Radon measurements at Jungfraujoch were sometimes influenced by boundary-layer air that reached the station through processes like thermally driven (anabatic) mountain winds. These findings suggest that both topographical characteristics and atmospheric dynamics can greatly affect radon distribution. This underscores the importance of considering the interaction between topography and atmospheric processes when evaluating radon levels across different geographical areas (Rey et al., 2023).

Instruments and methods for radon assessment

There are several methods and techniques for measuring radon levels in workplace environments and general surroundings. Due to the varying expected radon concentrations and exposure durations in these different settings, specialized approaches are necessary for accurate assessment (Kholopo & Rathebe, 2024).

Instruments for radon assessment

Modern radon measurement techniques are typically classified into two categories: passive and active methods. Each category presents unique advantages and limitations, making them suitable for various evaluation requirements (Mphaga, Mbonane, et al., 2024). Research comparing active and passive radon measurement techniques has emphasized that active techniques generally offer greater accuracy and reliability across different environments, including educational institutions and residential settings (Abojassim, 2020).

Active technique

Active techniques for radon measurement involve the use of electronic devices that continuously monitor and analyze radon levels in real time. These techniques provide ongoing data and are often used for precise and immediate assessments. Here are some common active radon measurement techniques: (Čeliković et al., 2022).

Scintillation cells (Lucas cell): Scintillation cells, commonly called Lucas cells, were created by Lucas in 1957. These devices are hermetically sealed metal containers that contain the air sample for analysis. There are two primary methods for introducing air into the cell (Shaw, 2005). The cell used in this method is a metal cylinder with one end closed by a transparent window. To prevent radon decay products from contaminating the cell, the incoming air is usually filtered. Once the cell is filled, the radon decay products reach secular equilibrium with the parent radon. For each radon decay, three alpha particles are emitted within the cell: The internal surfaces of the cell are treated with a scintillator, commonly ZnS(Ag), which reacts with alpha particles emitted by radon-222, polonium-218, and polonium-214 to generate light pulses. These light pulses are then detected by a photomultiplier tube and the relevant electronics. To enable continuous sampling, air can either be actively pumped through the chamber or allowed to passively diffuse in through a light-tight barrier (M.S, 2023).

Ionization chamber: An electric field is established between two or more electrodes in ionization chamber. Filtered air can enter the chamber either through passive diffusion or active pumping. The resulting current, generated by the ionization of the gas within the chamber, is then detected and measured.(CHOPPIN et al., 2002). The ionization detected in these chambers is caused by the decay of radon and its decay products. Measurement can capture each ionization in the chamber or focus on individual alpha particle pulses. The latter method allows for distinguishing between pulses from different decay products and radon itself. By configuring the system to reject counts from polonium-214, which is the final and most energetic decay product with alpha particles at 7.7 MeV, a quick reaction time can be achieved. Furthermore, the response time of the instrument is affected by how quickly air is exchanged in the ionization chamber. Recently, commercial ionization chambers have gained popularity as secondary standards in radon calibration laboratories (Studnička et al., 2019).

Scintillation counting in liquid: Liquid scintillation technique is a widely used approach for quantifying low-energy alpha- and beta-emitting radioisotopes. It provides high counting efficiency for isotopes frequently involved in chemical and biological processes, such as ^{3}H, ^{14}C, ^{32}P, ^{35}S and ^{131}I requires relatively simple sample preparation. This technique is particularly effective for measuring turnover and incorporation across various environments (Schubert & Kallmeyer, 2023). Liquid scintillation counting relies on specialized scintillation cocktails, which are mixtures of organic aromatic compounds and a suitable solvent. Radioactive isotopes decay and emit particles that excite the aromatic solvent, causing it to absorb energy and elevate electrons to excited states. These excited electrons then return to their ground state, emitting photons in the process. The photons are identified by photomultiplier tubes (PMTs), which convert them into electrical pulses. The amplitude of each pulse correlates with the decay energy of the isotopes. These electrical pulses are quantified and processed by the liquid scintillation analyzer's software to provide the final detected signals (Quantitation et al., 2004). The diversity of liquid scintillation counting makes it applicable across various fields, including medicine, meteorology, and physical sciences. Although there is extensive literature available on the technique and its functionality, it predominantly focuses on these primary application areas (US NRC, 2011).

Passive technique

Passive techniques for radon exposure measurement do not require active components or external power to operate. Instead, they rely on the accumulation of radon over time to assess exposure levels. Here are some common passive methods: (Mb et al., n.d.).

Charcoal detectors

Activated charcoal is capable of adsorbing various gases, including radon. When radon is adsorbed onto the charcoal, it undergoes decay, and the resulting decay products are retained. This allows for the measurement of the adsorbed radon through gamma spectrometry, specifically by detecting emissions from lead-214 and bismuth-214. Another technique for measurement is liquid scintillation counting. In this method, charcoal that has absorbed radon is combined with a liquid scintillation cocktail, which efficiently dissolves the radon. The resulting solution can then be analyzed using conventional liquid scintillation counting equipment (Maier et al., 2021). The detectors typically feature a layer of granulated activated charcoal contained within a metal canister, which is secured by a metal mesh and has a removable lid. Prior to use, the open canister is heated to eliminate any adsorbed gases and moisture. After this heating process, the lid is firmly taped in place, and the canister is taken to the measurement location, where the lid is removed to allow access to the charcoal. Once the exposure period concludes, the lid is reattached and secured, and the canister is sent back to the laboratory for analysis (Alves et al., 2021). Charcoal detectors do not function as true integrators because the radon that adsorbs at the beginning of an exposure period will decay and partially desorb throughout that time. To minimize desorption, a diffusion barrier can be placed between the charcoal bed and the surrounding climate.

Assessments are typically conducted during a timeframe of 2 to 7 days, which aligns with radon's 3.82-days half-life; extending the measurement duration becomes ineffective due to desorption. While charcoal detectors can accurately measure radon concentrations, their main limitation in assessing radon levels in dwellings is that concentrations fluctuate over an extended interval, making the results less reflective of the long-term mean (Živanović et al., 2020).

Electret ion chambers

Electrets function similarly to permanent magnets, but in the electrostatic domain, as they retain a stable surface charge that can produce a surface potential of several kilovolts. In practical applications, a Teflon electret is often placed at the bottom of a conducting plastic chamber, known as an Electret Ion Chamber (EIC). When radon gas enters the chamber, it ionizes the air, a process driven by radon and its decay products. This ionization leads to a loss of charge from the electret, as the ions neutralize the charge on the electret's surface. The resulting reduction in charge provides a direct measure of radiation levels, allowing for effective monitoring of radon-induced radiation (Kotrappa, 2008). This detector serves as a genuine time integrator for measuring radon exposure, though it does have a limited dynamic range. It is available with two electret elements that differ in thickness and sensitivity, as well as three distinct chamber sizes. The devices are sensitive to gamma rays, necessitating the application of a compensation factor. To ensure the most accurate measurements, adjustments for elevation should also be considered to account for fluctuations in atmospheric pressure (Usman, 1999). When utilizing these devices, it is crucial to adhere strictly to the instructions for preparing and reading the electrets. Any dust on the charged surface or dropping the Electret Ion Chamber (EIC) onto a hard surface can lead to partial discharge of the electret. This may result in an inaccurate and inflated estimate of radon exposure (Dua et al., 2002).

Etched track detectors

Etched track detectors employ plastic materials to record the trajectories of alpha particles emitted by radon and its decay products. The damage caused by these particles can later be revealed by treating the plastic with a solution of sodium hydroxide (NaOH) or potassium hydroxide (KOH), often supplemented with ethanol for enhanced effectiveness (El-Badry & Al-Naggar, 2018).

Three widely used materials for measuring radon levels are LR-115, polycarbonate, and CR-39 (also known as poly allyl diglycol carbonate, or PADC). LR-115 features a thin layer of colored cellulose nitrate that is mounted on an inert backing. Polycarbonate detectors undergo a process called electrochemical etching, which involves applying an alternating voltage during etching to reveal tracks created by ionizing radiation. Similarly, CR-39 is a plastic material that reacts to ionizing radiation. A comparative study assessing the performance of various laboratories in international tests of passive radon detectors found that LR-115, polycarbonate, and CR-39 all deliver accurate and reliable radon measurements. This demonstrates that each of these materials is effective for monitoring radon levels, with consistent performance across different testing environments (S. Singh & Prasher, 2004).

Techniques for Evaluating Occupational and Environmental Radon Exposure

Various methods and techniques are available for measuring radon levels in both workplace and residential environments. Since these settings vary in terms of expected radon concentrations and duration of exposure, different approaches are required to accurately assess the levels (Kholopo & Rathebe, 2024).

Techniques for Evaluating Radon Exposure in Occupational Settings

Assessing radon exposure in occupational settings includes measuring radon levels in indoor workspaces and evaluating the potential risks to workers. The techniques used for this assessment encompass a range of approaches, including long-term and short-term monitoring, grab sampling, radon exposure modeling, dosimetry, continuous real-time monitoring, radon mapping, and evaluations of indoor air qualit(Silva & Dinis, 2022). Long-term and short-term monitoring techniques evaluate radon levels across different timeframes: long-term monitoring extends from several months to a year, whereas short-term monitoring generally occurs over a period of a few days (Dicu et al., 2024). These methods are effective at capturing average radon concentrations and tracking fluctuations over time. In contrast, grab sampling, which involves collecting air samples at specific intervals, is less frequently employed in occupational environments because it does not effectively reflect the fluctuations in radon levels that take place during the workday (HASSAN et al., 2016). Radon exposure modeling employs computer simulations and mathematical frameworks to predict potential radon exposure for workers, considering variables such as ventilation rates, building features, and work-related activities. This approach complements direct measurement techniques by offering valuable insights into various exposure scenarios (Pawade & Charhate, 2024). Radon dosimetry requires workers to wear dosimeters that monitor their individual radon exposure over a specified timeframe, while continuous real-time monitoring employs automated instruments to deliver constant readings of radon concentration (Shahrokhi & kovács, 2023). The least commonly utilized approach is radon mapping, which entails creating a spatial representation of radon concentrations in workplace or public settings (Idriss et al., 2020). Certain studies integrate indoor air quality evaluations with radon monitoring to assess radon levels in conjunction with other indoor air contaminants, including carbon dioxide, volatile organic compounds, and particulate matter (Tunyagi et al., 2020).

Radon in mining settings

The risks of radon exposure are significantly greater in mining environments compared to typical commercial and residential environments (Brobbey et al., 2022). Miners employed in ore, uranium, and thorium mines face an increased risk of exposure to radon progeny, which are the radioactive decay products of radon. When these particles are inhaled, they can adhere to lung tissue, substantially elevating the likelihood of developing lung cancer (Thorne, 2020). This heightened risk arises from both the level and duration of radon exposure. As a result, the health impacts of radon exposure in occupational environments are complex, affecting not only the physical health of miners but also shaping health and safety regulations within the mining sector (UNSCEAR, 2020). Riudavets et al. (2022) demonstrated a linear relationship between radon exposure and lung cancer, indicating that increasing radon levels directly raise the risk of developing lung cancer. This insight highlights the unique occupational hazards faced by miners, emphasizing the necessity for effective safety measures and monitoring in mining environments (Riudavets et al., 2022).

Techniques for Evaluating Radon Exposure in Environmental settings

Investigating radon assessment in environmental contexts is essential for comprehending the potential health risks linked to radon exposure. (Esan, Obed, et al., 2020). Given that radon is a major contributor to lung cancer in non-smokers, the importance of strong assessment strategies cannot be overstated. These strategies are essential for identifying areas with elevated radon levels and for guiding the development and implementation of effective mitigation measures to safeguard public health. (Lantz et al., 2013). Charcoal canisters and continuous radon monitors are utilized in short-term monitoring, frequently employed in environmental contexts, to assess radon concentrations over a duration of 2 to 7 days Long-term monitoring, frequently used in environmental settings, employs alpha track detectors or electret ion chambers to measure radon concentrations over an extended duration, typically ranging from 3 months to 1 year (Kotrappa, 2021). In contrast, grab sampling entails gathering air samples for a brief period (ranging from minutes to several hours) using containers like activated charcoal canisters or sampling bags. These samples are subsequently analyzed in a laboratory to assess the radon concentration (Papp & Dezso, 2006). Soil gas monitoring is an essential technique for measuring radon levels in the soil. This method includes approaches such as soil gas probe sampling or sub-slab sampling, which are followed by laboratory analysis of the collected samples to evaluate radon concentrations (K. P. Singh et al., 2023). Furthermore, building diagnostics employ a range of methods and tools to evaluate radon levels within buildings. These approaches encompass real-time monitoring, both passive and active dosimeters, as well as radon mapping techniques (Pulinets et al., 2024).

Health effects of radon gas on humans

Lung cancer

The connection between radon exposure and the risk of lung cancer differs markedly between occupational exposure among underground miners and residential exposure within the general population (Liu et al., 2022).

5.1.1 Lung cancer susceptibility in underground miners

Since the 1960s, numerous epidemiological studies have examined lung cancer risk among underground miners. Typically, these studies measure the concentrations of radon progeny to which miners are exposed using two key metrics: "working level (WL)" and "working level month (WLM)"(Madas et al., 2022). WL is defined as the concentration of short-lived radon progeny in 1 liter of air that can potentially release 1.3 x 10^8 MeV of alpha energy from decay. (J. K. Kang et al., 2019). WLM (Working Level Month) is defined as the total exposure an individual receives to a concentration of 1 WL over the course of a 170-hour work month. One WLM roughly equals the radiation dose received by a person living in a home with a radon concentration of 227 Bq/m³ for one full year (WHO, 2007). Table 4 showcases a selection of key studies exploring the relationship between radon exposure and lung cancer risk among underground miners with occupational exposure (Richardson et al., 2022).

Table 4: Radon Exposure and Lung Cancer Risk among Underground Miners with Occupation (J. K. Kang et al., 2019)

Country	Author	Year of Publication	Sample Size	Person- Year of Exposure	No. of Lung Cancer Cases	ERR/100 WLM (95% CI)
Combined study	BEIR IV	1988	22562	433019	459	1.3 (0.8, 2.3)
	1CPR 65	1993	31486	635022	1047	1.34(0.82, 2.13)
	BEIR VI	1999	60606	888906	2674	0.55(0.27, 1.13)
	USCEAR	2009	128634	3246467	5715	0.59(0.3,1.00)
	Lane, et al	2019	Low cumulative radon exposure 100 WLM	394236	408	2.2(1.3, 3.4)
Canada	Keil, et al.	2015	4124	130000	617	1.17(1.15, 1.17)
Czech Republic	Tomasek	2012	9978	308910	1141	0.97(0.74, 1.27)
France	Rage, et al.	2018	5400	186994	211	0.73(0.32, 1.33)
Germany	Kreuzer, et al	2015	5504	158383	159	3.39(-0.01, 6.78)
Sweden	Jonsson, et al.	2010	5486	170204	122	2.20(0.23, 3.77)

ERR, excess relative risk; WLM, working level month; CI, confidence interval; BEIR, Biological Effects of Ionizing Radiations; ICRP, International Commission on Radiological Protection; UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation.

The initial thorough investigation into the correlation between radon exposure and lung cancer risk among underground miners was presented in the BEIR IV report on the Biological Effects of Ionizing Radiations. This report encompassed cohort studies involving miners from various locations, including Colorado, Ontario, Eldorado, and Malmberget (Kelly-Reif et al., 2023). The BEIR IV report indicated an excess relative risk of 1.3 per 100 WLM (95% confidence interval: 0.8–2.3). Five years later, the International Commission on Radiological Protection (ICRP) released the ICRP 65 report, which included some overlapping epidemiological studies with those from the BEIR IV report, specifically cohorts from Colorado, Ontario, Eldorado, and Malmberget. Additionally, the ICRP 65 report introduced new studies from Bohemia, New Mexico, and France. The reported excess relative risk in the ICRP 65 was 1.34 (95% CI: 0.82–2.13), which is comparable to the findings of the BEIR IV report (Health Protection Agency, 2009). The excess relative risk per 100 WLM was determined to be 1.34 (95% CI: 0.82–2.13), which is closely aligned with the results of the BEIR IV report. In 1999, the BEIR IV report was expanded to incorporate 11 cohort studies involving more than 60,000 miners, culminating in the publication of the BEIR VI report. This later report indicated an excess relative risk per 100 WLM of 0.55 (95% CI: 0.27–1.13) (Kreuzer et al., 2008). The BEIR VI report also investigated various factors that influence relative risk, including the time elapsed since exposure, age at the time of exposure, and the rate of exposure. It revealed that miners who were exposed to radon at a younger age and at lower concentrations experienced a more significant increase in lung cancer mortality per WLM compared to their counterparts. Following the BEIR VI report, a more detailed analysis was presented in the 2006 report by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (Laurier et al., 2020). The UNSCEAR 2006 report indicated an excess relative risk of 0.59 per 100 WLM (95% CI: 0.35–1.00). Following this, the ICRP 115 report proposed a detriment-adjusted nominal risk coefficient of 5×10^{-4} per WLM (or 14×10^{-5} per mJ h/m³) for lung cancer related to radon and its decay products, nearly doubling the figure from the earlier ICRP 65 report. Consequently, the recommended maximum reference level for indoor radon was lowered from 600 Bq/m³ to 300 Bq/m³, correlating to an annual effective dose of 4 mSv in workplaces and 14 mSv in residential environments (Saunders, 1981).

Lung cancer risk in the general population associated with radon exposure in homes

Given the established link between occupational radon exposure in miners and an increased risk of lung cancer, It is likely that residential exposure within the general population could also contribute to a higher risk of lung cancer (Reddy et al., 2022). However, it is important to recognize the significant uncertainty in directly extrapolating the findings from underground miners to the general population. The specific characteristics of the underground miner cohort, combined with variations in smoking behaviors and exposure to other harmful substances such as arsenic and quartz, both of which are associated with lung cancer may affect risk assessments for the general population (Services, 2002).

Epidemiological studies investigating the link between residential radon exposure and lung cancer risk in the general population typically measure the average radon concentration in indoor air, expressed in becquerels per cubic meter (Bq/m³) or picocuries per liter (pCi/L), with 1 pCi/L equivalent to 37 Bq/m³. These measurements are taken over the course of an individual's time spent in the residence (Dai et al., 2019).

Diseases other than lung cancer due to radon

Radon exposure is widely recognized for its association with an increased risk of cancer, particularly lung cancer. However, emerging research suggests that the health impacts of radon extend beyond cancer and can also influence non-cancerous diseases, such as Chronic Obstructive Pulmonary Disease (COPD). COPD is a progressive lung disease that causes breathing difficulties and includes conditions like emphysema and chronic bronchitis. Research has shown a potential link between radon exposure and the development or exacerbation of COPD (Grzywa-Celińska et al., 2020) . This association is thought to be due to the harmful effects of radon's radioactive particles, which, when inhaled, can irritate and damage lung tissues. Over time, this damage can contribute to the onset or progression of COPD. The relationship between radon exposure and COPD is particularly concerning for long-term residents in areas with high radon concentrations, especially in poorly ventilated indoor environments like basements and homes with radon infiltration. Studies suggest that prolonged exposure to radon can compromise the lung's ability to clear irritants, leading to respiratory problems and worsening the symptoms of COPD(Turner et al., 2012). One of the notable findings in this area is the observed increased hospitalization rates for respiratory conditions, particularly among women. Women, due to biological and lifestyle factors, may be more susceptible to the negative health effects of radon exposure. The correlation between radon exposure and increased hospitalization suggests that radon may exacerbate existing respiratory conditions, making individuals more vulnerable to acute health events like severe COPD exacerbations or infections. These findings underscore the need for greater awareness and mitigation efforts regarding radon exposure, not only to prevent cancer but also to protect public health against non-cancerous respiratory diseases such as COPD. Addressing radon risks could potentially reduce the burden of COPD-related hospitalizations, particularly among vulnerable populations like women and individuals with pre-existing respiratory conditions. (Conde-Sampayo et al., 2020). Miners exposed to radon have an elevated risk of mortality from conditions such as silicosis and pulmonary fibrosis. Furthermore, there is a significant correlation with end-stage renal disease associated with diabetic nephropathy (SLR Consulting Australia, 2020). Schubauer-Berigan and colleagues identified a correlation between cumulative exposure to silica and cumulative exposure to radon, both of which are linked to the duration of employment in mining. The authors observed a significant gradient in standardized mortality ratios for silicosis in relation to radon exposure. This finding suggests that miners with higher radon levels likely encountered increased silica exposures, particularly during earlier periods when silica control measures were less stringent (Kelly-reif et al., 2021). Alternatively, pulmonary diseases linked to radon exposure may have been misdiagnosed as silicosis. This misattribution could explain the higher standardized mortality ratios for silicosis observed in groups with elevated working level months (WLM) (Kelly-Reif et al., 2022). Studies have identified a link between exposure to high levels of radon and the occurrence of congenital malformations, such as cleft lip and palate, as well as cystic lymphangioma (MICHA, 2017). A search for a correlation between radon exposure and neurodegenerative diseases, particularly multiple sclerosis, was conducted. However, studies by Groves-Kirkby et al. found no statistically significant relationship (Groves-Kirkby et al., 2016).

Research conducted in Kazakhstan, a region abundant in uranium mines, revealed a higher incidence of fertility issues among women and an increased prevalence of urinary tract diseases and chronic bronchitis in children (Saifulina et al., 2023). Villeneuve et al. explored the relationship between radon exposure and heart disease; however, their research results remain inconclusive (Villeneuve et al., 2007). Gutiérrez-Avila and colleagues found a correlation between increased mortality from cardiovascular and respiratory diseases and elevated concentrations of PM2.5 and radon. They observed that PM2.5 could serve as a carrier for radon, facilitating its movement to the bronchial tree (Gutiérrez-avila et al., 2023).

It is important to recognize that water serves as a major source of radon. Radon can transfer from water to air, and when it comes to drinking water, it can also be absorbed through the digestive system (El-Araby et al., 2019). The National Research Council estimates that approximately 30% of radon-222 that reaches the stomach is absorbed into the stomach lining, suggesting its potential involvement in the development of stomach cancer (Auvinen et al., 2005). Numerous studies have examined the relationship between radon concentrations in drinking water and the incidence of gastrointestinal malignancies; however, their findings have been inconsistent (Yitshak-Sade et al., 2019).

Mitigation factors to radon effect

Minimizing radon exposure is crucial for lowering the risk of lung cancer and ensuring good indoor air quality. Various methods and approaches are utilized to effectively reduce radon levels in residential and other indoor spaces (Abed et al., 2024). In this section, we will discuss methods for reducing radon levels in both homes and water (United States Environmental Protection Agency, 2013). Figure 3 illustrates various mitigation strategies designed to minimize radon emissions from household appliances and decrease indoor radon concentrations. It features methods such as ventilation systems, sealing of cracks and openings, installation of radon detectors, and the use of radon-resistant construction materials. Each strategy is paired with a concise description that highlights its effectiveness, cost implications, and implementation factors. This figure serves as an essential tool for homeowners, builders, and regulatory authorities, helping them make informed choices to protect indoor air quality and public health (Nunes et al., 2024).

Methods for mitigating radon concentration in homes

Reducing radon levels in homes involves employing a variety of techniques to bring indoor radon concentrations down to safe and acceptable levels. These methods are usually implemented following radon testing that indicates elevated levels. The choice of a particular mitigation strategy is influenced by factors such as the construction of the building, the detected radon concentration, and the preferences of the homeowner. Below are some common techniques for lowering radon levels in homes (Spasić et al., 2024),(Benavente et al., 2019),(Alonso et al., 2019):

Sub slab ventilation system: is one of the most widely used and effective methods for mitigating radon gas in homes. It works by installing a vent pipe beneath the foundation slab, which is connected to a radon fan that creates negative pressure beneath the home. This negative pressure draws radon-laden soil gas from under the foundation, preventing it from infiltrating the indoor air. The gas is then safely vented outdoors, usually through an exhaust pipe that extends above the roofline. This system is highly efficient in reducing radon levels, often achieving a 50% to 99% reduction, making it one of the most reliable and long-term solutions for radon mitigation. Additionally, it operates with minimal maintenance and low energy consumption, making it both a cost-effective and sustainable choice for homeowners in radon-prone areas.

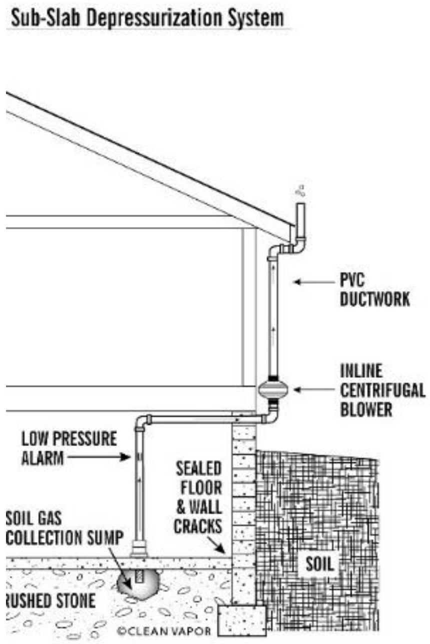

Figure 4: Illustration of sub slab depressurization (Alonso et al., 2019)

Sub-membrane ventilation system: Similar to the sub-slab ventilation system, the sub-membrane ventilation system is used in homes with crawl spaces rather than full basements. In this approach, a plastic membrane is placed over the soil or gravel in the crawl space, with a vent pipe attached to the membrane. A radon fan generates negative pressure beneath the membrane, effectively blocking radon from entering the home.

Block wall ventilation system: For homes constructed with block walls, radon mitigation can include drilling holes into the walls to set up a vent pipe system. This technique establishes negative pressure within the block walls, which helps to prevent radon from infiltrating the living spaces. By creating this pressure difference, radon gas is drawn away from the interior of the home, significantly reducing the risk of exposure.

Sealing fissures and penetrations: For maintaining a safe home environment, minimizing entry points for radon is crucial. Sealing cracks in the floors, foundation, and walls is one effective method that can significantly reduce the infiltration of radon gas. Although sealing is a vital step, its effectiveness is often enhanced when combined with other mitigation strategies, providing better overall protection against radon exposure.

Pressurization of house and rooms: When traditional radon mitigation methods are not feasible, pressurization techniques can be employed to establish positive pressure within the home, effectively preventing radon from entering. This strategy utilizes fans to bring in fresh air into the living areas, which helps to push out radon-contaminated air and creates a healthier indoor environment. By maintaining this positive pressure, the risk of radon infiltration is significantly reduced.

It is essential to have radon mitigation performed by certified professionals who are trained to accurately assess and address radon concerns. Proper installation and ongoing maintenance of mitigation systems are crucial for ensuring their long-term effectiveness.

Methods for mitigating radon levels in water

Methods for mitigating radon levels in water primarily include aeration and granular activated carbon (GAC) treatments. Here's a summary of these techniques (Ghernaout, 2019).

Aeration

Aeration involves facilitating contact between air and water to achieve several objectives. Specifically, it facilitates the diffusion of unwanted water pollutants into the air and promotes the oxidation of different forms of natural organic matter (NOM) (Venterea & Rolston, 2023), Improving water treatability is significantly aided by aeration, which plays a crucial role in water treatment processes. It effectively reduces taste and odor compounds, such as hydrogen sulfide and various synthetic volatile organic compounds (VOCs). Additionally, by removing carbon dioxide, aeration decreases corrosivity and lowers lime demand during lime softening processes. Furthermore, it facilitates the oxidation of iron and manganese, thereby enhancing overall water quality (Mendez-Ruiz et al., 2023). However, specifically utilizing aeration to manage radon levels is a relatively new concept in the drinking water industry (Commission, 2002).

The primary factor affecting the mass transfer of radon from water to air is the disparity between the existing concentration of radon in the water and the concentration that represents equilibrium between the gas and liquid phases (Cinelli et al., 2019). Henry's Law states that at a given temperature, the concentration of a solute in water is directly proportional to its concentration in the air (*Henry'S Law.Pdf*, n.d.).

Henry's Law states that the amount of gas that dissolves in a specific volume of solution is directly proportional to the partial pressure of that gas above the solution, provided the temperature and total pressure remain constant (Manitoba Education, 2013). Henry's law is represented by Equation (1).

$$p = \frac{HC}{PT} \qquad (1)$$

where:

p = mole fraction of the gas in air (moles of gas/moles of air)

C = mole fraction of the gas in water (moles of gas/moles of water)

H = Henry's Law constant (atm)

P T = total pressure (atm, typically equal to 1) (Ghernaout, 2019).

Since P T is often approximated as 1, Equation

$$p = HC \qquad (2)$$

As a result, H becomes dimensionless. Thus, $H = p/C$ (3)

Or $C = p/H$ (4)

A greater Henry's constant indicates a higher equilibrium concentration of the pollutant in the air. When a pollutant achieves saturation in both the liquid and vapor phases, its partial pressure is directly related to P v / S P v /S (where P v P v is the vapor pressure of the liquid and S denotes the solubility of the contaminant in water). This means that pollutants with lower solubility and/or higher volatility (i.e., increased vapor pressure) will demonstrate a higher Henry's Law constant. (Sander, 2015). The Henry's Law constant for radon in water at 20°C is 2.26×10^3 atm, which translates to 40.7 L-atm/mole and is equivalent to 5.09×10^{17} pCi/L-atm. This relationship is based on the fact that 6.48 mg of radon corresponds to an activity of 1 Curie (Ghernaout, 2019). Because of its high Henry's Law constant, radon easily moves from water to the air above it. At 20°C, ammonia (NH_3) has a Henry's Law constant of 0.76 atm, while carbon dioxide (CO_2) has a Henry's Law constant of 1.51×10^3 atm (Was & Nh, 2012). Radon's comparatively high Henry's Law constant indicates that it can diffuse from water into the air more rapidly than ammonia and carbon dioxide, both of which are gases that can be easily removed.

Granular activated carbon (GAC)

In the potable water treatment industry, the use of Granular Activated Carbon (GAC) has primarily been limited to monitoring synthetic organic chemicals and compounds affecting taste and odor (Ritson & Graham, 2019). However, after the detection of radon in drinking water sources, a variety of research studies and pilot-scale experiments have been carried out to assess the efficacy of Granular Activated Carbon (GAC) for monitoring and eliminating radon (Alabdula'aly & Maghrawy, 2011).

Radon is removed from water through the adsorption process using Granular Activated Carbon (GAC) (Jastaniah et al., 2014). The adsorption process takes place when radon molecules move from the water and adhere to the surface of Granular Activated Carbon (GAC). Radon is captured at the boundary between the water and the carbon material. Consequently, having a high surface area is essential for improving the efficiency of adsorption (WQA, 2013). While the outer surface of carbon contributes to adsorption, the majority of its surface area is situated within the pores of its internal structure (Saleem et al., 2019).

Adsorption systems typically operate in a downward flow configuration, with contaminated water entering at the top of the carbon bed and moving downward through the bed until it reaches the bottom (Patel, 2019). As water moves downward through the bed, radon is captured by the carbon until all available surface area for adsorption is filled. The radon continues to flow with the water through the bed until there is no longer any accessible area for additional adsorption (Heinitz et al., 2023). The removal of pollutants relies on the available interfacial area between the water and carbon, as well as the duration of contact time (Satyam & Patra, 2024).

Conversely, the disposal of used granular activated carbon (GAC) filters used in residential radon removal from well water raises concerns Radon removal from different types of groundwater applying granular activated carbon filtration (Turtiainen et al., 2000). The residual radioactivity accumulated on the filter media, including natural uranium, radium, and lead, must be taken into account to mitigate concerns at the disposal site (Marques et al., 2021). It is well established that well water contains trace amounts of uranium, radium, and radon, and the performance of GAC filters varies in their ability to remove each of these contaminants. Additionally, lead, a decay product of radon, will also accumulate on the filter (Tyrväinen et al., 2023).

CONCLUSION

Radon, a naturally occurring radioactive gas from uranium decay in soil and rock, poses significant risks to indoor air quality and public health. Factors such as soil permeability and architectural design influence radon entry into homes, potentially leading to hazardous accumulation. Prolonged exposure can cause severe health issues, particularly lung cancer, which accounts for 15,000 to 22,000 deaths annually in the U.S., making radon the second leading cause of lung cancer after smoking. Both smokers and non-smokers are at risk, emphasizing the need for effective testing and mitigation strategies, including sub-slab ventilation systems, enhanced ventilation, and public awareness campaigns. Addressing radon exposure requires a multi-faceted policy approach, including regulations on building codes, mandatory testing in high-risk areas, and increased funding for research and public education. Future research should focus on the long-term effects of radon exposure and developing more effective mitigation methods. By advancing knowledge, improving mitigation techniques, and enacting policies that prioritize radon reduction, we can protect public health and create safer living environments.

Future perspective

Radon, a naturally occurring radioactive gas from uranium decay in soil and rock, poses significant health risks, particularly lung cancer, especially among smokers. Its migration into homes is influenced by factors such as soil composition, weather conditions, and building design, which can trap the gas indoors. Detection methods have evolved from simple passive detectors to advanced continuous monitoring systems, improving the accuracy of radon level assessments. Mitigation strategies, including radon-resistant construction techniques and active ventilation systems, are essential for reducing indoor concentrations. As awareness of radon's dangers grows, future efforts will focus on emerging detection technologies, such as more sensitive and cost-effective sensors, and potential regulatory developments, including stricter building codes and mandatory testing in high-risk areas. Additionally, public education will play a critical role in minimizing exposure and safeguarding health. By advancing these efforts, we can better protect communities from radon's harmful effects.

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