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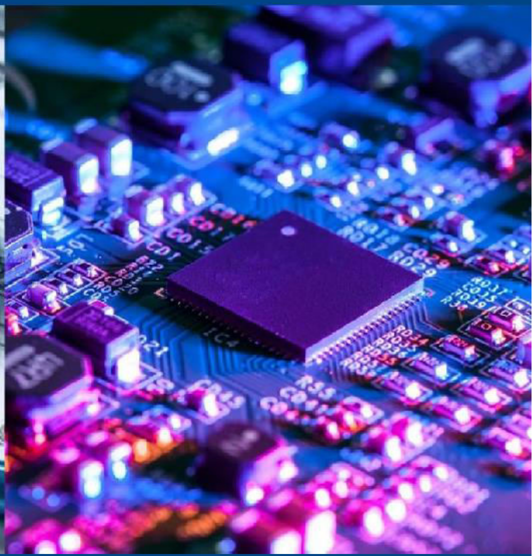

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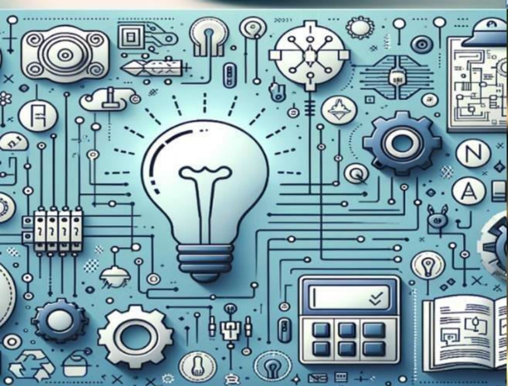

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Assessment of Indoor and Outdoor Natural Radon Radioactivity and Its Environmental Impact in Residential and Public Buildings

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ABSTRACT: Natural radon radioactivity represents a significant environmental concern in both residential and public buildings due to its potential for accumulation in indoor spaces and its contribution to overall environmental radiation exposure. This assessment examines the patterns of indoor and outdoor radon concentrations across different categories of buildings, highlighting the marked contrast between elevated indoor levels and relatively lower outdoor concentrations. Indoor environments, particularly in lower floors and structures with limited ventilation, tend to exhibit higher radon accumulation influenced by building materials, design features, and air exchange rates. Outdoor radon levels remain comparatively moderate and are primarily governed by natural dispersion processes. The comparative evaluation reveals consistently higher indoor-to-outdoor ratios, underscoring the role of building envelopes in trapping radon. From an environmental perspective, the findings indicate that radon contributes meaningfully to local radioactivity burdens, with implications for air quality in and around built structures. Prolonged occupancy in residential and public buildings may lead to increased radiological exposure, particularly for sensitive groups. Overall, the assessment emphasizes the environmental significance of radon dynamics in the built environment and the need for attention to indoor accumulation patterns and their broader ecological and health-related consequences.

KEYWORDS: Natural radon radioactivity; Indoor radon; Outdoor radon; Residential buildings; Public buildings; Environmental impact; Radiological exposure.

I. INTRODUCTION

Natural radon is a radioactive noble gas that occurs universally as a product of the natural decay of uranium-238 present in soil, rocks, and many geological formations. Being chemically inert, colourless, and odourless, radon remains undetectable by human senses, yet it continuously migrates from its source materials into the surrounding environment. Once released into the pore spaces of soil or the matrix of building materials, radon atoms move through diffusion and advection processes and eventually enter both outdoor air and the interior spaces of buildings. Because of its relatively short half-life and the subsequent formation of solid radioactive decay products, radon constitutes a distinctive component of natural environmental radioactivity that interacts directly with human living and working environments.

Residential buildings and public buildings form the principal settings of daily human occupancy. Houses, apartments, schools, offices, hospitals, libraries, and community centres enclose large volumes of air in which radon can accumulate over time. In outdoor environments, radon disperses relatively freely under the influence of wind, atmospheric mixing, and temperature gradients, resulting in generally lower and more variable concentrations. Indoors, however, the same gas tends to become trapped. Limited air exchange rates, the presence of cracks and openings in foundations, the use of radon-bearing construction materials such as concrete, brick, and stone, and the continuous supply of radon from underlying soil all contribute to elevated indoor levels. The contrast between indoor accumulation and outdoor dispersion is therefore a fundamental characteristic of radon behaviour in the built environment.

The environmental significance of this contrast extends beyond simple concentration differences. Indoor spaces function as semi-closed systems that can concentrate radon to levels several times higher than those found outdoors. This concentration process alters the local radioactive burden of air within buildings and, through ventilation and air exchange, influences the immediate outdoor surroundings as well. Over time, the continuous release of radon from soil and building materials into indoor air, followed by its partial discharge into the outdoor atmosphere, creates a dynamic exchange that

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links the radiological quality of indoor environments with that of the broader outdoor environment. In densely built areas, the cumulative effect of numerous residential and public structures can contribute measurably to the overall environmental radioactivity of the locality.

Several physical and structural factors govern the magnitude of indoor radon accumulation. Building design plays a critical role: ground-floor and basement spaces typically exhibit higher concentrations because of their closer proximity to the soil source. Construction materials that contain elevated levels of uranium or radium can themselves act as internal sources of radon. Ventilation practices further modulate indoor levels; buildings with poor air exchange or those sealed for energy conservation often retain higher concentrations, while well-ventilated structures tend to maintain lower indoor values closer to outdoor background. Seasonal variations also influence the pattern, with colder periods frequently associated with higher indoor concentrations due to reduced natural ventilation and increased pressure-driven inflow of soil gas.

Public buildings present additional considerations. Schools, hospitals, and offices often accommodate large numbers of people for extended periods and may feature complex ventilation systems, multiple occupancy zones, and varying construction standards. The prolonged presence of individuals in such spaces raises the importance of understanding radon distribution across different functional areas within the same building. Residential buildings, by contrast, involve continuous or near-continuous occupancy by the same individuals, making the cumulative exposure over time particularly relevant. In both categories of structures, the interplay between outdoor radon levels and indoor accumulation determines the overall exposure environment experienced by occupants.

From an environmental perspective, radon represents more than an indoor air quality issue. It forms part of the natural radioactive continuum that connects geological materials, soil gas, outdoor atmosphere, and indoor air. The movement of radon across these compartments contributes to the spatial distribution of environmental radioactivity and influences the radiological characteristics of urban and semi-urban landscapes. Elevated indoor concentrations can lead to the release of radon and its decay products into outdoor air through exhaust systems and natural leakage, thereby affecting the immediate outdoor environment around buildings. Conversely, outdoor radon serves as a background reference against which indoor elevations can be evaluated, providing a basis for assessing the degree of accumulation attributable to building-related factors.

The radiological implications of these patterns are closely linked to environmental conditions. Radon and its short-lived decay products, when inhaled, deliver radiation dose primarily to the respiratory system. In environments where indoor concentrations remain consistently elevated relative to outdoor levels, the potential for increased cumulative exposure rises, particularly for individuals who spend the majority of their time indoors. Sensitive groups, including children in schools and patients in healthcare facilities, may experience relatively higher exposure because of both occupancy duration and physiological factors. The environmental impact of radon, therefore, encompasses not only the alteration of air quality within and around buildings but also the associated implications for human exposure in everyday residential and public settings.

Understanding the patterns of indoor and outdoor natural radon radioactivity is essential for a comprehensive assessment of its environmental role in the built environment. The marked differences between indoor and outdoor concentrations, the influence of building characteristics, and the continuous exchange between these two compartments together define the environmental behaviour of radon. By examining these aspects in residential and public buildings, it becomes possible to evaluate the contribution of radon to local environmental radioactivity, to identify the conditions that promote accumulation, and to recognise the broader significance of indoor–outdoor contrasts for environmental quality and exposure potential. Such an assessment provides a foundation for recognising radon as an integral component of the natural radioactive environment that interacts continuously with human-made structures and the surrounding atmosphere.

II. INDOOR RADON CONCENTRATION PATTERNS

Indoor environments in residential and public buildings create conditions that favour the accumulation of natural radon to levels substantially higher than those typically found outdoors. Once radon enters a building through the foundation, floor slabs, walls, or service penetrations, its movement becomes constrained by the limited volume of enclosed air and the restricted rate of air exchange with the outdoor atmosphere. As a result, indoor radon concentrations commonly display a characteristic elevation that reflects both the continuous supply of the gas from underlying soil and building materials and the incomplete removal of the gas through ventilation.

In residential buildings, concentration patterns show marked vertical and spatial variation. Ground-floor and basement spaces consistently record higher values because of their direct contact with the soil source. Radon-bearing soil gas enters these lower levels under the influence of pressure differences that develop between the indoor air and the outdoor atmosphere, particularly during colder periods when indoor heating creates a stack effect. Upper floors generally exhibit progressively lower concentrations as the distance from the soil source increases and as air mixing within the building dilutes the gas. Room-to-room differences also appear; spaces with limited natural or mechanical ventilation, such as bedrooms with closed windows, storerooms, and poorly aired living areas, tend to retain higher levels, while kitchens and bathrooms with more frequent air exchange often show comparatively lower values.

Building age and construction characteristics further shape indoor patterns. Older residential structures frequently contain more cracks, joints, and gaps in foundations and walls, providing additional entry pathways for soil gas. Modern buildings, although often better sealed for energy efficiency, may still experience elevated concentrations if the sealing reduces air exchange without adequately addressing radon entry points. Construction materials themselves contribute an internal source. Concrete, brick, stone, and certain types of gypsum or aggregates can release radon directly into indoor air, adding to the contribution from soil. The combined effect of external soil entry and internal material emanation produces the overall indoor concentration profile observed in residential settings.

Public buildings display both similarities and distinctive features in their indoor radon patterns. Schools, offices, hospitals, and community centres typically encompass larger floor areas, multiple occupancy zones, and more complex ventilation systems than individual dwellings. Ground-floor classrooms, administrative offices, and waiting areas often register higher concentrations, reflecting the same proximity to soil sources seen in residential buildings. However, the presence of mechanical ventilation systems can significantly modify these patterns. Well-maintained systems that provide adequate outdoor air supply tend to reduce indoor levels, whereas systems that recirculate air with minimal fresh-air intake may allow concentrations to rise. In multi-storey public buildings, the vertical gradient remains evident, yet the distribution can be less uniform because of centralised air-handling units, stairwells, and lift shafts that facilitate air movement between floors.

Occupancy patterns also influence the observed concentrations. Public buildings experience intermittent use, with periods of high occupancy during working or school hours alternating with periods of reduced activity. During occupied hours, doors and windows may be opened more frequently, and mechanical systems operate at higher capacity, often resulting in temporary reductions in radon levels. Overnight and weekend periods, when buildings are closed and ventilation is minimised, allow concentrations to rebuild. Residential buildings, by contrast, maintain more continuous occupancy, so the concentration patterns reflect a more stable balance between continuous radon entry and the prevailing ventilation regime of the household.

Seasonal variation constitutes another important dimension of indoor radon behaviour. During colder months, buildings are more tightly closed, natural ventilation decreases, and the indoor–outdoor temperature difference enhances the inflow of soil gas. Consequently, indoor concentrations frequently reach their highest values in winter. Warmer months generally bring lower indoor levels as windows remain open for longer periods and natural air exchange increases. This seasonal cycle is observable in both residential and public buildings, although the amplitude of variation may differ according to the effectiveness of mechanical ventilation systems and the climatic conditions of the region.

The physical behaviour of radon inside buildings further contributes to the observed patterns. Being denser than air, radon tends to accumulate in lower portions of rooms under still-air conditions, although normal air movement from human activity, heating systems, and convection currents usually produces a more uniform vertical distribution within a given space. In poorly ventilated rooms, however, localised pockets of higher concentration can persist near floor level or in corners with limited air circulation. These micro-scale variations add complexity to the overall indoor concentration field.

So, indoor radon concentration patterns in residential and public buildings reveal a consistent tendency toward elevation relative to outdoor background levels. The magnitude of this elevation depends on a combination of geological source strength, building design and materials, ventilation practices, occupancy behaviour, and seasonal climatic influences. Ground-level spaces, poorly ventilated rooms, and structures with limited air exchange emerge as the primary zones of

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higher accumulation. Understanding these patterns is essential for evaluating the contribution of indoor environments to the overall environmental radioactivity associated with natural radon and for recognising the conditions that most strongly promote its retention within the built environment.

III. OUTDOOR RADON CONCENTRATION PATTERNS

Outdoor environments surrounding residential and public buildings exhibit distinctly different radon behaviour compared with indoor spaces. In the open atmosphere, radon released from soil and surface materials disperses rapidly under the influence of wind, atmospheric turbulence, and vertical mixing. As a result, outdoor radon concentrations generally remain lower and more variable than those recorded indoors, reflecting the continuous dilution of the gas once it enters the free atmosphere.

Near the ground surface, outdoor radon levels are influenced primarily by the rate of exhalation from soil. Soil characteristics such as porosity, moisture content, and uranium content govern the quantity of radon that escapes into the air. Dry, porous soils tend to release higher amounts of radon, while wet or compacted soils restrict its upward movement. Once released, the gas mixes with ambient air, and its concentration decreases with height above the ground. Measurements close to the surface typically show higher values than those taken at greater elevations, where atmospheric mixing is more effective.

Spatial variation in outdoor radon is also evident around buildings. Areas immediately adjacent to structures may experience slightly elevated concentrations because of the contribution of radon seeping from foundations, walls, and outdoor drainage systems. Courtyards, narrow passages between buildings, and sheltered zones with reduced air movement can retain higher outdoor levels than open, well-ventilated spaces. In contrast, open grounds, parks, and areas exposed to prevailing winds usually display lower and more uniform concentrations. The presence of vegetation, paved surfaces, and local topography further modifies the spatial distribution by affecting soil exhalation and air circulation patterns.

Temporal fluctuations form another important feature of outdoor radon behaviour. Diurnal variations are commonly observed, with higher concentrations often occurring during the night and early morning hours when atmospheric stability is greater and vertical mixing is reduced. During the day, solar heating increases turbulence and disperses radon more effectively, leading to lower daytime values. Seasonal changes also influence outdoor levels. In colder periods, frozen or snow-covered ground can limit soil exhalation, while in warmer and drier seasons the release of radon from soil may increase. Rainfall events temporarily suppress outdoor concentrations by sealing soil pores, after which a rebound in exhalation often occurs as the soil dries.

Meteorological conditions play a decisive role in determining outdoor radon patterns. Wind speed and direction strongly affect dispersion: stronger winds dilute radon more rapidly, while calm conditions allow local accumulation near the ground. Temperature inversions, which trap air close to the surface, can lead to temporary elevations in outdoor concentrations. Atmospheric pressure changes also influence soil gas movement; falling pressure tends to draw more radon out of the ground, whereas rising pressure suppresses exhalation. These meteorological controls create a dynamic outdoor radon field that fluctuates continuously in response to changing weather conditions.

Around residential and public buildings, outdoor radon serves as the background reference against which indoor accumulation is assessed. The outdoor concentration represents the baseline level that enters buildings through ventilation systems, open windows, and structural openings. When outdoor levels rise due to atmospheric stability or increased soil exhalation, the potential for indoor entry also increases. Conversely, periods of strong atmospheric mixing reduce both outdoor concentrations and the driving force for radon entry into buildings. This continuous interaction between outdoor and indoor compartments underscores the environmental linkage between the two environments.

In densely built areas, the collective presence of numerous structures can subtly influence outdoor radon distribution. Buildings alter local wind patterns, create sheltered micro-environments, and contribute small additional amounts of radon through leakage from indoor spaces and outdoor exhaust systems. Although these contributions are generally minor compared with soil exhalation, they add complexity to the outdoor concentration field in urban and semi-urban settings. Open spaces between buildings and the orientation of streets relative to prevailing winds further shape the local outdoor patterns.

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outdoor radon concentration patterns are characterised by lower average values, greater spatial and temporal variability, and strong dependence on soil properties, meteorological conditions, and local topography. Unlike the relatively stable and elevated levels found indoors, outdoor concentrations reflect the free dispersion of radon in the atmosphere and the continuous interplay between soil sources and atmospheric mixing processes. These outdoor patterns provide the essential environmental context for understanding indoor accumulation and for evaluating the broader contribution of natural radon to environmental radioactivity in the vicinity of residential and public buildings.

IV. COMPARATIVE EVALUATION OF INDOOR AND OUTDOOR LEVELS

The comparison between indoor and outdoor natural radon concentrations reveals a consistent and environmentally significant contrast that defines the behaviour of this radioactive gas in the built environment. While outdoor levels remain relatively low due to continuous atmospheric dispersion, indoor concentrations in both residential and public buildings are characteristically elevated, often by several times the outdoor background. This difference arises from the fundamental distinction between the open atmosphere, where radon disperses freely, and the enclosed spaces of buildings, where the gas accumulates under restricted air exchange conditions.

Indoor-to-outdoor concentration ratios provide a clear quantitative expression of this contrast. In residential buildings, these ratios commonly indicate that indoor levels exceed outdoor values by a substantial margin, particularly on lower floors and in spaces with limited ventilation. The ratio tends to be highest in ground-floor rooms and basements, where proximity to the soil source and reduced air movement combine to maximise accumulation. On upper floors the ratio decreases, yet indoor concentrations still remain higher than concurrent outdoor levels. Public buildings display similar patterns, although the magnitude of the indoor-to-outdoor ratio can vary according to the efficiency of mechanical ventilation systems and the frequency of air exchange during occupied hours. In structures with inadequate fresh-air supply, the ratio remains elevated, while well-ventilated public buildings may show more moderate differences.

Several interconnected factors explain the persistent elevation of indoor concentrations relative to outdoor background. The continuous supply of radon from soil beneath and around buildings creates a steady influx that is not fully offset by ventilation. Pressure differences between indoor and outdoor air, generated by temperature gradients, wind effects, and mechanical systems, further drive soil gas into the building interior. Once inside, radon is retained by the limited volume of indoor air and the incomplete replacement of that air with outdoor air. Construction materials add an internal source that operates independently of outdoor conditions, reinforcing the indoor elevation. In contrast, outdoor radon is subject to immediate dilution by wind and atmospheric turbulence, preventing sustained accumulation except under unusual conditions of atmospheric stability.

The comparative patterns also highlight important differences between residential and public buildings. Residential structures, with their more continuous occupancy and often more limited mechanical ventilation, tend to maintain relatively stable indoor elevations above outdoor levels throughout the day and night. Public buildings experience greater fluctuation in the indoor-to-outdoor relationship because of intermittent occupancy and the periodic operation of ventilation systems. During occupied periods, increased air exchange can reduce the indoor concentration and narrow the gap with outdoor levels. During unoccupied periods, when systems are switched off or set to minimum, indoor concentrations rise again and the ratio widens. Despite these operational differences, both categories of buildings consistently show higher indoor than outdoor radon levels under most conditions.

Seasonal variations further illuminate the indoor–outdoor contrast. In colder months, reduced natural ventilation and stronger pressure-driven inflow of soil gas increase indoor concentrations while outdoor levels may simultaneously decline due to limited soil exhalation under cold or frozen conditions. The result is a widening of the indoor-to-outdoor ratio. In warmer months, greater use of open windows and natural air movement lowers indoor levels and brings them closer to outdoor values, reducing the ratio. These seasonal shifts demonstrate that the indoor–outdoor relationship is dynamic and responsive to climatic influences that affect both compartments differently.

Spatial comparisons within and around buildings reinforce the same overall pattern. Indoor spaces nearest the ground and those with the poorest air exchange display the greatest elevation above outdoor background. Immediately outside the building, outdoor concentrations remain lower, although they may show slight local increases near foundation edges or in sheltered courtyards. As distance from the building increases and exposure to free atmospheric mixing improves, outdoor levels decline further toward regional background values. This spatial gradient from high indoor concentrations

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through intermediate near-building outdoor values to lower open-air levels illustrates the progressive influence of dispersion processes.

The environmental significance of the indoor–outdoor contrast lies in the continuous exchange that occurs between the two compartments. Outdoor air entering a building through ventilation, windows, or structural openings carries the prevailing outdoor radon concentration, while indoor air leaving the building exports the higher indoor concentration into the surrounding atmosphere. This two-way exchange links the radiological quality of indoor environments with that of the immediate outdoor surroundings. Although the quantity of radon released from indoor spaces into outdoor air is generally small compared with direct soil exhalation, it contributes to the local environmental radioactivity field around buildings and forms part of the broader cycling of natural radon in the built environment.

So, the comparative evaluation of indoor and outdoor radon levels demonstrates a clear and persistent elevation of concentrations inside residential and public buildings relative to outdoor background. The indoor-to-outdoor ratio serves as a reliable indicator of accumulation, reflecting the combined effects of soil gas entry, building characteristics, ventilation regimes, and seasonal climatic influences. This contrast underscores the role of buildings as environments that concentrate natural radon and highlights the environmental linkage between indoor accumulation and outdoor dispersion processes. Understanding these comparative patterns is essential for assessing the contribution of the built environment to local environmental radioactivity and for recognising the conditions under which indoor elevations become most pronounced.

IV. ENVIRONMENTAL IMPACT ASSESSMENT

The presence of natural radon in and around residential and public buildings generates a range of environmental impacts that extend beyond simple concentration differences. As a radioactive component of the natural environment, radon participates in continuous exchanges between soil, outdoor air, and indoor spaces, thereby influencing the radiological quality of the built environment and its immediate surroundings. The accumulation of radon indoors and its subsequent interaction with outdoor air create a dynamic system that contributes to local environmental radioactivity and alters the characteristics of air quality in occupied areas.

One of the primary environmental impacts arises from the role of buildings as concentrating environments. Residential and public structures intercept radon originating from soil and construction materials and retain it within enclosed volumes of air. This retention elevates the radioactive content of indoor air relative to the outdoor atmosphere and establishes buildings as localised zones of higher environmental radioactivity. Over time, the continuous inflow of radon and the incomplete removal of the gas through ventilation sustain these elevated indoor levels, creating persistent radioactive micro-environments within the broader landscape. In densely built areas, the collective effect of numerous such structures can contribute to a measurable increase in the overall radioactive burden of the locality.

The exchange of air between indoor and outdoor compartments further shapes the environmental impact. When indoor air containing higher radon concentrations is released through windows, doors, exhaust systems, or structural leakage, it introduces additional radioactivity into the immediate outdoor surroundings. Although the quantity involved is generally modest compared with direct soil exhalation, this process links indoor accumulation directly to outdoor air quality near buildings. Conversely, outdoor air entering buildings carries the prevailing background concentration indoors, establishing a continuous two-way transfer that integrates the radiological conditions of both environments. This exchange ensures that changes in outdoor radon levels, driven by meteorological or soil conditions, influence indoor environments, while indoor accumulation simultaneously affects the near-building outdoor atmosphere.

Soil–building interactions constitute another significant pathway of environmental impact. Buildings modify the natural movement of soil gas by covering portions of the ground surface, altering local pressure regimes, and creating preferential pathways for radon entry through foundations and service penetrations. These modifications can enhance the release of radon from soil into indoor spaces while simultaneously influencing the pattern of outdoor exhalation around the building perimeter. In this way, the presence of residential and public structures redistributes natural radon fluxes, concentrating a portion of the soil-derived radioactivity indoors and altering its spatial distribution outdoors.

Air quality implications form a central aspect of the environmental impact. Elevated indoor radon concentrations degrade the radiological quality of air within occupied spaces, introducing a continuous source of alpha-emitting decay products

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that remain suspended or attach to aerosols. In outdoor environments near buildings, localised increases in radon can similarly affect the radioactive composition of ambient air, particularly under conditions of limited atmospheric mixing. The combined indoor and outdoor effects contribute to the overall environmental radioactivity to which both building occupants and the surrounding outdoor environment are exposed.

Long-term environmental consequences arise from the persistent nature of these processes. Unlike many transient pollutants, radon is continuously generated by the decay of naturally occurring uranium in soil and building materials. As long as buildings remain in place, the mechanisms of entry, accumulation, and exchange continue to operate, sustaining the elevated indoor levels and the associated outdoor interactions. Seasonal and meteorological variations modulate the intensity of these processes but do not eliminate them. Over extended periods, the cumulative contribution of residential and public buildings to local environmental radioactivity becomes an enduring feature of the built landscape.

The environmental impact also encompasses the broader ecological context. Radon and its decay products form part of the natural radioactive continuum that connects geological materials with the atmosphere and human-made structures. By intercepting and redistributing this continuum, buildings influence the spatial patterns of environmental radioactivity and create gradients between high indoor concentrations, intermediate near-building outdoor levels, and lower open-air background values. These gradients reflect the environmental role of the built environment as both a receptor and a secondary source of natural radon.

In residential settings, the environmental impact is characterised by relatively stable indoor elevations and continuous air exchange with the outdoor surroundings of individual dwellings. In public buildings, the impact is shaped by larger spatial scales, more complex ventilation regimes, and intermittent occupancy patterns that produce greater temporal variation in the indoor–outdoor exchange. Despite these differences, both categories of buildings contribute to the same fundamental environmental processes: the concentration of radon indoors, the modification of soil-gas fluxes, and the linkage of indoor and outdoor radioactive air quality.

So, the environmental impact of natural radon radioactivity in residential and public buildings is expressed through the elevation of indoor air radioactivity, the alteration of local outdoor air quality, the redistribution of soil-derived radon fluxes, and the establishment of persistent radioactive micro-environments within the built landscape. These impacts arise from the inherent physical behaviour of radon and the structural characteristics of buildings, forming an integral component of the environmental radioactivity associated with human habitation and public infrastructure. Recognition of these impacts provides a basis for understanding the contribution of the built environment to the broader natural radioactive system.

V. RADIOLOGICAL EXPOSURE AND IMPACT CONSIDERATIONS

The patterns of indoor and outdoor natural radon radioactivity in residential and public buildings carry direct implications for radiological exposure. Because radon and its short-lived decay products emit alpha radiation, their presence in inhaled air contributes to the radiation dose received primarily by the respiratory system. The magnitude of this exposure depends on the concentration of radon in the air, the duration of occupancy, the breathing rate of individuals, and the degree to which decay products are attached to aerosols or remain unattached. In both residential and public buildings, the elevated indoor concentrations relative to outdoor background create conditions under which cumulative exposure can become significant over time.

Indoor environments represent the dominant pathway of radon-related exposure for most individuals. Residential buildings, where people spend a large proportion of their time, particularly during night-time hours when ventilation is often reduced, contribute substantially to long-term cumulative dose. Ground-floor living spaces and bedrooms frequently associated with higher radon levels further increase the potential exposure for occupants. Continuous or near-continuous presence in these spaces means that even moderate elevations above outdoor background can result in meaningful annual radiation doses. Public buildings add a complementary component of exposure. Schools, offices, hospitals, and other institutional structures accommodate large numbers of people for substantial portions of the day. Although occupancy is intermittent, the duration of stay during working or school hours, combined with the possibility of elevated indoor concentrations in certain zones, contributes to the overall exposure profile of the population.

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The relative contribution of residential versus public building exposure varies according to individual activity patterns. For many people, the home environment accounts for the greater share of total radon exposure because of the longer hours spent indoors. However, for children attending school, workers in offices, patients in healthcare facilities, and staff in public institutions, the contribution from public buildings can become appreciable. In cases where both residential and public buildings exhibit elevated indoor levels, the combined exposure from the two environments increases the total radiological burden. Outdoor exposure, by contrast, remains comparatively low because of the generally lower outdoor concentrations and the shorter periods spent in open air. Nevertheless, outdoor radon forms the baseline against which indoor elevations are measured and contributes a continuous, though smaller, component of environmental exposure.

Sensitive groups experience particular considerations in relation to radon exposure. Children, with their higher breathing rates relative to body size and longer remaining lifetime, may receive higher effective doses from the same concentration levels. Patients in hospitals and residents of care facilities often spend extended periods indoors with limited mobility, increasing their cumulative exposure. Individuals living or working predominantly on lower floors of buildings face greater potential exposure because of the typical vertical gradient in radon concentrations. These differential impacts highlight the importance of recognising occupancy patterns and building characteristics when evaluating the radiological consequences of indoor radon.

The environmental dimension of radiological exposure is closely linked to the continuous exchange between indoor and outdoor air. Higher indoor concentrations increase the amount of radon and decay products that can be exhaled into the outdoor environment, while outdoor air entering buildings introduces the prevailing background concentration. This exchange ensures that radiological conditions in one compartment influence those in the other. In areas with numerous residential and public buildings, the collective indoor accumulation can subtly elevate the local outdoor radioactive air quality, creating a shared environmental exposure field that affects both building occupants and individuals spending time outdoors near structures.

Temporal variations further modulate exposure patterns. Seasonal increases in indoor radon during colder months coincide with periods when people spend more time indoors, potentially amplifying cumulative dose during winter. Diurnal fluctuations in outdoor concentrations and corresponding changes in indoor levels linked to ventilation practices also influence short-term exposure rates. Over the course of a year, these variations produce a fluctuating but persistent exposure regime that reflects the dynamic behaviour of radon in the built environment.

The radiological impact extends beyond individual dose to encompass broader environmental health considerations. Elevated indoor radon contributes to the overall radiation environment experienced by populations in residential and public settings. The presence of alpha-emitting decay products in indoor air represents a continuous source of internal radiation exposure that is distinct from external radiation sources. Because this exposure occurs in the spaces where people live, learn, work, and receive care, it forms an integral part of the environmental radiation background associated with modern built environments.

The radiological exposure associated with natural radon in residential and public buildings arises primarily from elevated indoor concentrations, is modulated by occupancy duration and building characteristics, and is linked to outdoor background levels through continuous air exchange. Residential environments typically dominate long-term cumulative exposure, while public buildings contribute additional dose during periods of institutional occupancy. Sensitive groups and occupants of lower-floor spaces face heightened potential impacts. These exposure considerations form a direct consequence of the indoor–outdoor radon patterns and the environmental processes that govern radon behaviour in the built environment, underscoring the significance of indoor accumulation for both individual and collective radiological conditions.

V. DISCUSSION OF FINDINGS

The assessment of indoor and outdoor natural radon radioactivity in residential and public buildings reveals a coherent set of patterns that highlight the distinctive behaviour of this radioactive gas within the built environment. The consistent elevation of indoor concentrations above outdoor background levels emerges as the central finding, reflecting the fundamental difference between enclosed spaces that favour accumulation and open atmospheres that promote dispersion. This contrast is not incidental but arises directly from the physical properties of radon, the continuous supply from soil and building materials, and the structural characteristics of residential and public buildings.

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Indoor concentration patterns demonstrate clear vertical and spatial organisation. Lower floors and poorly ventilated rooms systematically record higher values, while upper floors and better-aired spaces show progressive reduction. These internal gradients indicate that proximity to the soil source and the effectiveness of air exchange are the dominant controls on indoor accumulation. Public buildings exhibit similar tendencies, yet the influence of mechanical ventilation systems introduces greater temporal variability, with concentrations declining during periods of active air exchange and rising again when systems operate at reduced capacity. Residential buildings, characterised by more continuous occupancy and often more limited mechanical ventilation, maintain relatively stable elevated levels. Together, these observations confirm that building design, construction materials, and ventilation regimes exert strong control over indoor radon behaviour.

Outdoor concentration patterns present a contrasting picture of lower average values and higher variability. Dispersion driven by wind, atmospheric turbulence, and vertical mixing prevents the sustained accumulation observed indoors. Spatial differences around buildings remain modest, with only slight elevations near foundations or in sheltered zones, while temporal fluctuations follow diurnal and seasonal cycles linked to atmospheric stability and soil exhalation rates. The outdoor environment therefore functions as a dynamic background against which indoor elevations can be evaluated, providing the reference level that enters buildings through natural and mechanical ventilation.

The comparative evaluation of indoor and outdoor levels quantifies the extent of accumulation through indoor-to-outdoor ratios. These ratios remain elevated across both residential and public buildings, confirming that structures systematically concentrate radon relative to the surrounding atmosphere. Seasonal shifts further illustrate the responsiveness of the indoor–outdoor relationship: colder periods widen the ratio through increased indoor accumulation and reduced outdoor levels, while warmer periods narrow it through enhanced natural ventilation. The persistence of the indoor elevation under most conditions underscores the role of buildings as environments that intercept and retain natural radon.

Environmental impact considerations arise directly from these concentration patterns. Buildings modify the natural flux of radon by covering soil surfaces, creating pressure-driven entry pathways, and establishing enclosed volumes in which the gas accumulates. The subsequent exchange of air between indoor and outdoor compartments redistributes a portion of this accumulated radioactivity into the near-building atmosphere, linking indoor conditions with local outdoor air quality. Over time, the collective presence of residential and public structures contributes to the spatial organisation of environmental radioactivity, producing gradients from high indoor levels through intermediate near-building outdoor values to lower open-air background. These processes establish the built environment as an active component of the natural radioactive system rather than a passive receptor.

Radiological exposure implications follow from the same patterns. Elevated indoor concentrations, combined with prolonged occupancy in residential settings and substantial daily presence in public buildings, create conditions for meaningful cumulative radiation dose. The dominance of indoor exposure over outdoor exposure reflects the concentration differential and the greater time spent indoors. Sensitive groups and occupants of lower-floor spaces face comparatively higher potential impacts because of both concentration gradients and occupancy characteristics. The continuous air exchange between compartments ensures that radiological conditions remain environmentally linked, with indoor accumulation influencing outdoor air quality and outdoor background influencing indoor levels.

Collectively, the findings portray natural radon as a pervasive environmental constituent whose behaviour is strongly shaped by the presence of buildings. The indoor environment emerges as the primary zone of accumulation and exposure, while the outdoor environment provides the dispersive background and the medium of exchange. Building characteristics—particularly floor level, ventilation effectiveness, and construction materials—determine the magnitude of indoor elevation, while meteorological and soil conditions govern outdoor variability. The resulting indoor–outdoor contrast generates measurable environmental impacts through the redistribution of radioactivity and the creation of persistent radioactive micro-environments within the built landscape.

These patterns carry broader significance for understanding environmental radioactivity in human settlements. Residential and public buildings do not merely exist within a radioactive environment; they actively organise and concentrate a portion of natural radon, thereby modifying local radiological conditions. The assessment of indoor and outdoor levels, their comparative relationship, and the associated environmental and exposure consequences together provide an integrated view of radon dynamics in the built environment. Recognition of these dynamics is essential for

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appreciating the contribution of human-made structures to the natural radioactive continuum and for identifying the conditions under which indoor accumulation becomes most pronounced.

VI. RECOMMENDATIONS

Based on the observed patterns of indoor and outdoor natural radon radioactivity and their environmental implications, several practical measures can help reduce indoor accumulation and improve overall environmental conditions in residential and public buildings.

Improving ventilation remains one of the most effective approaches. Increasing natural air exchange through regular opening of windows and doors, particularly in lower-floor spaces and during periods of higher indoor concentrations, helps dilute accumulated radon. In public buildings, ensuring that mechanical ventilation systems supply adequate outdoor air and operate effectively during occupied hours can significantly lower indoor levels. Periodic inspection and maintenance of these systems are essential to sustain their performance.

Building design and construction practices also offer important opportunities for reduction. Attention to foundation integrity, sealing of cracks, joints, and service penetrations, and careful selection of construction materials with lower radon emanation potential can limit entry pathways. In new constructions, incorporating radon-resistant features such as proper sub-slab preparation and appropriate ventilation arrangements at the design stage provides long-term benefits. For existing buildings, targeted sealing and improved ground-floor ventilation can meaningfully reduce indoor concentrations.

Regular monitoring of indoor radon levels in both residential and public buildings is advisable, especially in ground-floor and basement spaces where accumulation tends to be highest. Periodic assessment allows early identification of elevated conditions and supports timely corrective action. Public institutions such as schools, hospitals, and offices should include radon considerations within routine environmental quality evaluations.

Awareness among building occupants and managers contributes to sustained improvement. Simple practices such as maintaining adequate air circulation, avoiding prolonged sealing of rooms, and recognising the influence of seasonal conditions can help keep indoor levels closer to outdoor background. In public buildings, operational schedules that align ventilation with occupancy patterns further support lower concentrations.

Finally, continued attention to the indoor–outdoor relationship remains important. Measures that reduce indoor accumulation simultaneously lessen the contribution of buildings to local outdoor radioactivity through air exchange. Integrating radon considerations into broader environmental and building-management practices strengthens the overall quality of both indoor and outdoor environments in residential and public settings.

VII. CONCLUSIONS

The assessment of indoor and outdoor natural radon radioactivity in residential and public buildings reveals a consistent elevation of indoor concentrations above outdoor background levels. This contrast arises from the continuous supply of radon from soil and building materials, combined with limited air exchange inside enclosed spaces, while outdoor levels remain lower due to effective atmospheric dispersion.

Indoor patterns show higher values on lower floors and in poorly ventilated rooms, with residential buildings maintaining relatively stable elevations and public buildings displaying greater fluctuation linked to ventilation and occupancy. Outdoor concentrations remain more variable and substantially lower under most conditions. Indoor-to-outdoor ratios stay elevated across both building types, widening in colder periods and narrowing with increased natural ventilation.

These patterns generate clear environmental impacts. Buildings concentrate natural radon, raise the radioactive content of indoor air, and through continuous air exchange influence local outdoor air quality near structures. The resulting indoor–outdoor gradients contribute to the spatial organisation of environmental radioactivity in the built landscape.

Radiological exposure follows primarily from the elevated indoor levels. Prolonged presence in residential settings and substantial daily occupancy in public buildings create conditions for meaningful cumulative dose, particularly for

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sensitive groups and lower-floor occupants. Outdoor exposure remains limited by lower concentrations and shorter time spent outdoors.

Overall, residential and public buildings actively organise natural radon by concentrating it indoors and linking indoor conditions with the surrounding outdoor environment. The indoor–outdoor contrast, together with its environmental and exposure consequences, underscores the significant role of the built environment in shaping natural radon radioactivity.

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