

Radon Concentration in Drinking Water Along Yagachi River Basin

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Abstract- In this study, the annual effective dose exposure in the Yagachi river basin and the distribution of radon activity concentration in drinking water samples are measured. Emanometry method was used to determine the radon concentration in 30 samples of drinking water. The observed radon concentration in drinking water samples ranged from 12.26 ± 0.21 to 118.56 ± 2.65 Bq l⁻¹ with an geometrical mean value of 45.24 ± 1.03 Bq l⁻¹. According to this study, all the drinking water samples examined had radon levels are above the USEPA's maximum contamination level of 11.1 Bq l⁻¹. The geometrical mean annual effective dose varies from 33.47 to 323.67 μ Sv y⁻¹ with geometrical mean value of 123.52 μ Sv y⁻¹. Annual effective doses of 73% drinking water samples are above the recommended limit of 100 μ Sv y⁻¹ recommended by World Health Organization.

Keywords: Radionuclides, Radon, Ingestion, Inhalation, Annual effective dose.

I. INTRODUCTION

Many scientists worldwide are very interested in estimating the natural radioactivity in soil, rock, building materials, and drinking water. The soil found in the top layer of the earth's crust is made up of organic matter, mineral particles, and living things are the most important natural resources [1]. Natural radioactivity and the associated external exposure to gamma radiation are primarily determined by geological and geographical circumstances. Almost all types of soils, rocks, drinking water, and building materials include the primordial radionuclides and their decay products [2].

Water is essential for life on Earth. The need for high-quality drinking water is critical for human health. Demand for pure and fresh water has increased in recent decades as a result of rapid population development, irregular rainfall, and increased human density. Contamination of water occurs as a result of increased industrial and human activity. Because of its transit through rocks and soil formations, as well as the dissolution of numerous chemicals, minerals, and radioactive contaminants, ground water is more radioactive.

The three naturally occurring radioactive series present in water are uranium, thorium, and actinium, among them, uranium radioactive series is

detrimental to human health since it is both chemically and radiotoxic [3]. ²²⁶Ra, ²²⁸Ra, and ²²²Rn are common radionuclides found in water that pose serious health risks to humans. They emit alpha particles, and their breathing in and ingestion can result in significant radioactive doses to sensitive cells in the pulmonary tracts, digestive systems, and other human organs [4]. The concentration of ²²²Rn in ground water depends on the hydrogeology of the area or aquifer, whereas it is very low in surface water, with concentrations of less than 4 Bq l⁻¹[5].

The ²²²Rn isotope has a half-life of 3.825 days in the human environment, which is long enough to cause lung cancer, stomach cancer, and leukaemia [6]. The potential health risk from radon enriched drinking water can be caused by two mechanisms: first, the transfer of ²²²Rn and its progenies liberated from water into indoor air and inhalation, and second, direct intake of dissolved ²²²Rn in potable water [6]. Considering the possible health risk of waterborne radon, approximately 89% of lung cancer caused by inhalation of ²²²Rn released from water and 11% of stomach cancer caused by consumption of ²²²Rn contaminated water [7]. ²²²Rn concentrations in drinking water, air, and soil were measured in various places of the world in order to calculate the annual effective dose and reduce the health risks of radon on humans [8-11].

The two possible health risks posed by radon-enriched drinking water are the transport of radon from water to indoor air and its inhalation as well as ingestion. Long-term population exposure to high levels of radon and its daughters results in pathological effects such as respiratory disorders and lung cancer [12]. Drinking water with a high ^{222}Rn level, on the other hand, may raise the risk of stomach cancer and gastrointestinal cancer [12]. Radon is the second leading cause of lung cancer in the United States, after smoking, according to the Environmental Protection Agency [13].

The USEPA proposed a maximum contamination limit (MCL) of 11.1 Bq l^{-1} for ^{222}Rn in water [13]. Understanding the activity concentration of ^{222}Rn in drinking water is critical for public health. As a result, the current work is the first attempt to determine ^{222}Rn content in drinking water along Yagachi river basin. As a result, a campaign to spread knowledge about drinking water use and its potential health risks has been launched in the current research area. The data from the current study will be added to the radon mapping in India's scientific data bank.

II. STUDY AREA

Yagachi river starts in Chikmagalur Baba Budan hill range and travels through Belur Taluk and Hassan District before ending. At Gorur, it joins with the Hemavathi river. Vothole is the main tributary to it. A Vothole dam has been built nearby Rajanahalli [14,15]. Latitudes $12^{\circ} 52' 58''$ to $13^{\circ} 25' 1''$ north and longitudes $75^{\circ} 59' 54''$ to $75^{\circ} 59' 54''$ east define the location of the Yagachi River in Karnataka, India. Its catchment area extends southward from Gorur Dam to Mullayyanagiri (Baba Budan Range). The towns of Belur, Chikmagalur, Arsikere, and Hassan receive irrigation and drinking water from Yagachi, similar as Vothole [14,15]. The research area measures around 116 km long. Peninsular gneiss is the most major rock type there, followed by charnokite, gneisses, unidentified crystallines, slates, phyllites, and schists [14,15]. Figure 1 shows the representation of the study area.

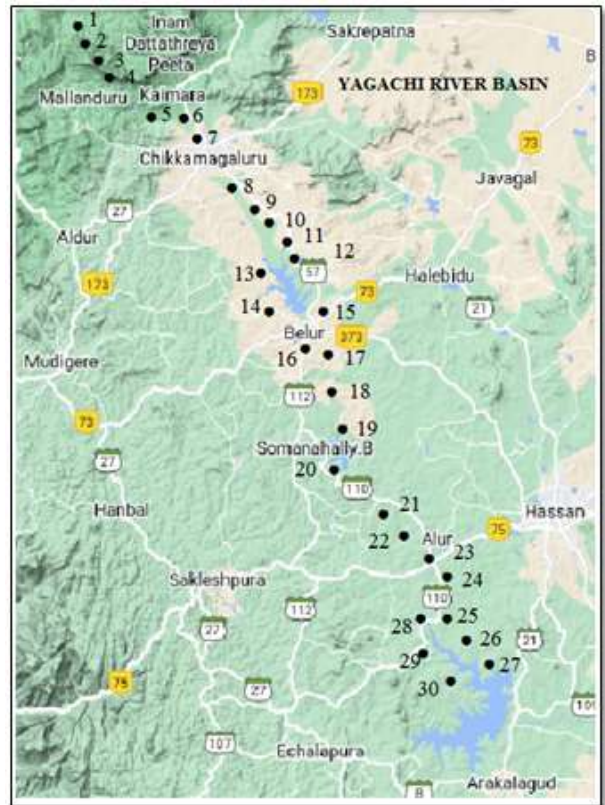


Figure1: Location map of the study area (Yagachi river basin).

III. MATERIALS AND METHODS

Samples collection and preparation

Water samples were collected from various locations in the Yagachi river basin, India from April to May 2023. Twenty two bore well water samples of 250 ml are collected after allowing water for 10 to 15 minutes of pumping and eight surface water samples were collected from public taps (river water) in specially prepared plastic bottles. While collecting water samples, bottles are filled and gently closed the cap without any air bubbles inside the container. Three samples were collected from each site to test the accuracy of radon concentrations. The collected water were sent to the laboratory to examine dissolved ^{222}Rn using the Emanometry method [16].

Determination of radon concentration by bubbler method

The Emanometry technique was used in this study to measure the ^{222}Rn concentration in drinking water

[21, 22]. Using a vacuum pump, the bubbler and scintillation cells were evacuated first, and then 60 to 70 ml of water was put into the bubbler. By bubbling the water inside the bubbler, the dissolved radon was transferred to the evacuated scintillation cell. After 3 hours of establishing equilibrium between ^{222}Rn and its progeny, the cell was alpha counted using an alpha detecting instrument. Figure 2 is a schematic diagram of a radon bubbler. The concentration of dissolved ^{222}Rn was determined using the formula [17].

$$\text{Concentration of radon } C_{Rn} \text{ (BqL}^{-1}\text{)} = \frac{6.97 \times 10^{-2} \times D}{V X E X e^{-\lambda T} X e^{-\lambda \theta} X (1 - e^{-\lambda t})} \quad (1)$$

where D denotes the difference in background and sample counts. V denotes volume of water, E denotes scintillation cell efficiency, and R is the radon decay constant ($2.09 \times 10^{-6} \text{ s}^{-1}$). T denotes the counting delay after sampling (seconds), t the counting duration (seconds), and θ the bubbler building time (seconds) [17].

Estimation of inhalation and ingestion dose

The two possible routes for ^{222}Rn in water entering the human body are inhalation and ingestion. Both the lungs and the stomach are susceptible to radon in the water. The radiation dose to the stomach (ingestion) is established by the amount of water consumed each day. The radiation dose to the lungs, on the other hand, is determined by the release of ^{222}Rn gas from water during normal human activity. Radiation exposure from waterborne radon is considered to be more harmful to the population than all other contaminants in water [18]. The UNSCEAR has published standard formulas for estimating annual effective doses of radon in water to people [18].

$$\begin{aligned} \text{Dose due to inhalation } E_{In} \text{ (}\mu\text{Sv y}^{-1}\text{)} \\ = C_{Rn} \times R_{aW} \times I \times O \\ \times K \quad (2) \end{aligned}$$

where R_{aW} is the ratio of ^{222}Rn in air to ^{222}Rn in water (10-4), I is the radon-progenies equilibrium

factor (0.4), O is the average indoor occupancy time per individual (7000 ha^{-1}), and K is the dosage conversion factor for radon exposure [$9 \text{ nSv (Bq h m}^{-3}\text{)}^{-1}$].

$$\begin{aligned} \text{Dose due to ingestion } E_{Ing} \text{ (}\mu\text{Sv y}^{-1}\text{)} \\ = C_{Rn} \times A_w \\ \times D \quad (3) \end{aligned}$$

where A_w denotes weight estimated water consumption (60 la^{-1}) and D is the effective dosage coefficient for ingestion (3.5 nSvBq^{-1}).

Estimation of age-dependent ingestion dose

The radiation dose to the stomach caused by ^{222}Rn exposure in water has been calculated for individuals of various ages using the equation given in the United Nations Scientific Committee on the Effects of Atomic Radiation [19].

$$\begin{aligned} \text{Total effective dose for ingestion } E_{Ing} \\ = C_{Rn} \times DWI \times F \times T \end{aligned}$$

DWI is daily water consumption for the general public of various age groups such as infants, children, males, females, pregnancy, and lactation. F and T are the dose conversion factor ($10^{-8} \text{ Sv Bq}^{-1}$) and exposure time (365 days per year), respectively [19].

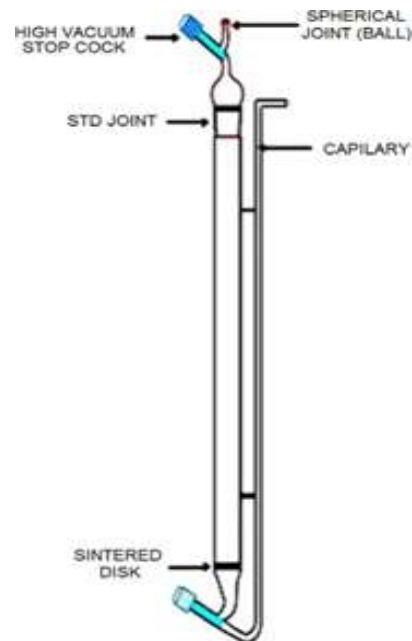


Fig.2 Schematic diagram of Radon bubbler [17]

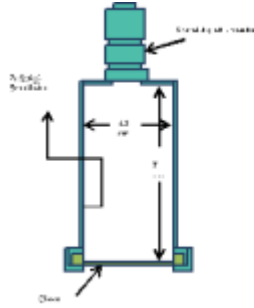


Fig.3 Schematic diagram of Scintillation cell (Lucas cell)[17]

IV. RESULTS AND DISCUSSION

222Rn activity in drinking water

In India, there are no special rules or regulations regarding the amount of radon in drinking water. Maximum Contamination Limits (MCL) for the concentration of 222Rn activity in water has been proposed by a number of international bureaus and organisations from the perspective of radiological protection. The USEPA proposed a maximum contamination level of 11.1 Bq l-1 for 222Rn concentration in groundwater in accordance with the safe drinking water act's directives in 1991 [13]. In 1999, it also proposed an alternative MCL of 150 Bq l-1 by taking into account the increase in 222Rn activity concentration in indoor air from water [20]. The World Health Organization advised that if the amount of 222Rn activity in drinking water was greater than 100 Bq l-1, some corrective action should be taken [21]. UNSCEAR recommended 222Rn activity levels in water in the range of 4 to 40 Bq l-1 for human consumption [22]. The Indian supervisory authority has not yet established a maximum contamination level or reference level for the presence of 222Rn in drinking water sources.

Table 1 summarises the estimated average 222Rn concentrations and equivalent effective dosage due to ingestion and inhalation by the general public in the Yagachi river basin. The 222Rn activity in the drinking water of the Yagachi river basin ranged from 12.26 ± 0.21 to 118.56 ± 2.65 Bq l-1 with a geometrical mean value of 45.24 ± 1.03 Bq l-1. The MCL of 11.1 Bq l-1 recommended by USEPA was exceeded by the geometrical mean radon activity levels of all locations [20]. It is also obvious that the

222Rn activity levels calculated in 100% of the examined area's drinking water is greater than the USEPA's recommended limit contamination level of 11.1 Bq l-1. The levels of 222Rn activity found in 84% of the analysed drinking water samples are lower than the 100 Bq l-1 recommended by the WHO [21]. Additionally, it is clear that radon activity levels in 26% of the drinking water samples were significantly below the UNSCEAR's maximum recommended limit of 40 Bq l-1[22].

The highest 222Rn activity was found in bore well water collected from Dattathreya Peeta this may be because old granite is present in that area. Due to the existence of old granitic at various depths and thrusts, faults, and shears that allow radon gas to migrate upward, higher activity concentration was also seen in the Malaguru, Melagiri, Jagara and Allampura [14,15]. The lower 222Rn activity concentration in water was observed at some locations, this may be due to the underlying bedrock system attributed by Quartz chlorite schist, lateritic, metabasic older gneiss rocks which contain lower activity concentration of radionuclides [14, 15].

The dependent elements for change of 222Rn activity in drinking water are the geo-hydrological characteristics of the aquifer and the geological region with high uranium/radium containing granite rock [23]. Along the broken surface, 226Ra rich minerals decay and emit 222Rn into the groundwater. The diverse depths of water resources and a different mechanism that affects the geo-hydrological nature of the locations are main causes for the differences in 222Rn concentration [23]. The Table 1 shows that bore well drinking water has a higher concentration of 222Rn than surface water. This might be because radionuclides like 238U and 226Ra are found in soil and rocks in varying amounts; as a result, radon can freely travel through porous rocks beneath saturated water tables. The radon that is present in the soil and rocks can easily dissolve into the water when it comes from these pores and be carried there with it. The deeper wells and hand pumps are another factor in the increasing radon levels. The concentration of 222Rn activity in the surface water was quite low. Because of the difference in ambient temperature, the surface water

is easily exposed and the dissolved radon is readily discharged to the atmosphere [24].

The Table 2 shows that all surface water samples, total annual effective dosage exposure was significantly below the WHO recommended threshold of 100 $\mu\text{Sv y}^{-1}$ as a result, the ^{222}Rn dose

received by the surface drinking water in the research area did not pose any health risks and all bore well water samples, total annual effective dosage exposure was above 100 $\mu\text{Sv y}^{-1}$ and will pose health risks to the residents [21].

Table 1 Concentration of radon in drinking water samples

Sl. NO.	Villages and Towns	Location		Sample type	C_{Rn} Bq l ⁻¹ Mean \pm SD
		Latitude	Longitude		
R1	Malaguru	13° 26' 14"	75° 42' 34"	Bore well water	115.32 \pm 2.34
R2	Melagiri	13° 29' 09"	75° 40' 28"	Bore well water	110.24 \pm 2.15
R3	Jagara	13° 26' 59"	75° 40' 25"	Bore well water	113.35 \pm 2.18
R4	Dattathreya peeta	13° 23' 21"	75° 43' 27"	Bore well water	118.56 \pm 2.65
R5	Allampura	13° 20' 36"	75° 45' 35"	Bore well water	112.32 \pm 2.34
R6	Indavara	13° 20' 38"	75° 45' 52"	Bore well water	87.47 \pm 1.87
R7	Chikkamagaluru	13°19' 51"	75° 46' 24"	Surface water	19.18 \pm 0.24
R8	Mugulavalli	13° 17' 07"	75° 48' 22"	Bore well water	56.37 \pm 1.24
R9	Matadathimmanahalli	13° 16' 02"	75° 47' 07"	Bore well water	49.46 \pm 1.13
R10	Hejjiganahalli	13° 15' 18"	75° 48' 40"	Bore well water	46.47 \pm 1.17
R11	Hosamane	13° 14' 29"	75° 49' 37"	Bore well water	49.45 \pm 1.20
R12	Narayanapur	13° 13' 50"	75° 49' 51"	Surface water	18.37 \pm 0.32
R13	Yamasandi	13° 13' 13"	75° 49' 33"	Surface water	19.47 \pm 0.43
R14	Bommadihalli	13° 11' 40"	75° 50' 17"	Bore well water	45.67 \pm 1.65
R15	Chikkabyadegere	13° 10' 44"	75° 52' 18"	Surface water	20.37 \pm 0.38
R16	Belur ,Villupuram	13° 09' 39"	75° 51' 58"	Surface water	21.54 \pm 0.45
R17	Belur, halebhidi	13° 09' 54"	75° 52' 03"	Surface water	19.38 \pm 0.26
R18	Chammadevanahalli	13° 08' 06"	75° 52' 41"	Bore well water	56.45 \pm 1.28
R19	Chalvegowdana Koppalu	13° 06' 01"	75° 53' 55"	Bore well water	43.45 \pm 1.36
R20	N. Koppalu	13°02' 36"	75° 53' 45"	Bore well water	58.54 \pm 1.43
R20	Haluvalli	13° 01' 10"	75° 55' 49"	Bore well water	56.36 \pm 1.46
R22	Imatipura	12° 59' 48"	75° 58' 10"	Bore well water	68.34 \pm 1.87
R23	Alur	12° 58' 29"	75° 59' 37"	Surface water	12.26 \pm 0.21
R24	Thuraganahalli	12° 55' 55"	76° 00' 01"	Bore well water	45.28 \pm 1.03
R25	Chattanahalli	12° 54' 21"	75° 59' 35"	Bore well water	43.37 \pm 1.38
R26	Kadabagala	12° 54' 00"	76° 00' 28"	Bore well water	51.38 \pm 1.42
R27	Chowdanahalli	12° 52' 21"	76° 02' 18"	Bore well water	47.39 \pm 1.52
R28	Honnenahalli	12° 53' 14"	75° 58' 48"	Bore well water	45.54 \pm 1.38
R29	Valagarahalli	12° 51' 28"	75° 59' 18"	Bore well water	49.37 \pm 1.42
R30	Garighatta	12° 50' 30"	76° 00' 04"	Surface water	22.24 \pm 0.45
Minimum					12.26 \pm 0.21
Maximum					118.56 \pm 2.65
Geometrical mean					45.24 \pm 1.03

Table 2 Annual effective dose in the drinking water samples

Sl. NO.	Villages and Towns	Din $\mu\text{Sv y}^{-1}$	Dose to lungs $\mu\text{Sv y}^{-1}$	Dig $\mu\text{Sv y}^{-1}$	Dose to stomach $\mu\text{Sv y}^{-1}$	AED $\mu\text{Sv y}^{-1}$
R1	Malaguru	290.61	34.84	24.22	2.90	314.82
R2	Melagiri	277.80	33.31	23.15	2.77	300.96
R3	Jagara	285.64	34.25	23.80	2.85	309.45
R4	Dattathreya peeta	298.77	35.82	24.90	2.98	323.67
R5	Allampura	283.05	33.94	23.59	2.82	306.63
R6	Indavara	220.42	26.43	18.37	2.20	238.79
R7	Chikkamagaluru	48.33	5.80	4.03	0.48	52.36
R8	Mugulavalli	142.05	17.03	11.84	1.42	153.89
R9	Matadathimmanahalli	124.64	14.94	10.39	1.24	135.03
R10	Hejjiganahalli	117.10	14.04	9.76	1.17	126.86
R11	Hosamane	124.61	14.94	10.38	1.24	135.00
R12	Narayanapur	46.29	5.55	3.86	0.46	50.15
R13	Yamasandi	49.06	5.88	4.09	0.49	53.15
R14	Bommadihalli	115.09	13.80	9.59	1.15	124.68
R15	Chikkabyadegere	51.33	6.15	4.28	0.51	55.61
R16	Belur ,Villupuram	54.28	6.51	4.52	0.54	58.80
R17	Belur, halebhidi	48.84	5.86	4.07	0.49	52.91
R18	Chammadevanahalli	142.25	17.06	11.85	1.42	154.11
R19	Chalvegowdana Koppalu	109.49	13.13	9.12	1.09	118.62
R20	N. Koppalu	147.52	17.69	12.29	1.47	159.81
R20	Haluvali	142.03	17.03	11.84	1.42	153.86
R22	Imatipura	172.22	20.65	14.35	1.72	186.57
R23	Alur	30.90	3.70	2.57	0.31	33.47
R24	Thuraganahalli	114.11	13.68	9.51	1.14	123.61
R25	Chattanahalli	109.29	13.10	9.11	1.09	118.40
R26	Kadabagala	129.48	15.52	10.79	1.29	140.27
R27	Chowdanahalli	119.42	14.32	9.95	1.19	129.37
R28	Honnenahalli	114.76	13.76	9.56	1.14	124.32
R29	Valagarahalli	124.41	14.92	10.37	1.24	134.78
R30	Garighatta	56.04	6.72	4.67	0.56	60.72
	Minimum	30.90	3.70	2.57	0.31	33.47
	Maximum	298.77	35.82	24.90	2.98	323.67
	Geometrical mean	114.02	13.67	9.50	1.14	123.52

For people of various ages, the ingestion dose was calculated based on annual water intake in order to determine the potentially harmful effects of radon on health. Table 3 provides a summary of the calculated total annual ingestion doses to individuals in various age groups. The annual effective ingestion dose in infants varies from 31.32 to 302.92 $\mu\text{Sv y}^{-1}$ with geometrical mean value of 115.60 $\mu\text{Sv y}^{-1}$, the fact that infants and children drink less water may be the reason why the geometrical mean ingestion dose exposure to ^{222}Rn in drinking water is significantly less. The annual effective ingestion dose in adults varies from 165.57 to 1601.15 with geometrical mean value of 611.02 $\mu\text{Sv y}^{-1}$, Adults drink 3.7 liters of water per day so radon ingestion dosage exposures was significantly high in adults [19].

Table 3 Annual effective ingestion doses due to radon in drinking water (Different age groups)

Life stage	Age group	DWI (L day ⁻¹)	Annual effective ingestion dose (μSv y ⁻¹)		
			Min	Max	Geo. Mean
Infants	0-6 months	0.7	31.32	302.92	115.60
	7-8 months	0.8	35.80	346.20	132.11
Children	1-3 years	1.3	58.17	562.57	214.68
	4-12 years	1.7	76.07	735.66	280.74
Males	9-13 years	2.4	107.40	1038.59	396.34
	4-18 years	3.3	147.67	1428.06	544.97
	Adults	3.7	165.57	1601.15	611.02
Females	9-13 years	2.1	93.97	908.76	346.80
	4-18 years	2.3	102.92	995.31	379.83
	Adults	2.7	120.82	1168.41	445.88
Pregnancy	19-50 Years	3	134.25	1298.23	495.43
Lactation	19-50 years	3.8	170.05	1644.43	627.54

V. CONCLUSION

According to the above mentioned findings, 100% of the examined area's drinking water exceeds the MCL of 11.1 Bq.l-1, as suggested by the USEPA. The 16% of the drinking water have 222Rn values are much higher than the 100 Bq.l-1 as suggested by the WHO. Divergent geological aquifers and geohydrological characteristics are the cause of the uneven distribution of 222Rn in drinking water of the studied area. Bore well drinking water samples had greater radon activity concentrations than Surface drinking water samples. When compared to lung tissues exposed to airborne, waterborne radon through breathing, the annual effective dose absorbed by stomach walls through ingesting was much lower. The annual effective dose received by the residents by bore well water is above 100 μSv y-1 and will pose health risks. Surface water is safe for drinking purpose and do not pose any health risks. Radon ingestion dosage exposures was significantly high in adults.

REFERENCES

- Girault, F., Perrier, F., & Przylibski, T. A. (2018). Radon-222 and radium-226 occurrence in water: a review. Geological Society, London, Special Publications, 451(1), 131-154.
- Ponciano-Rodríguez, G., Gaso, M. I., Armienta, M. A., Trueta, C., Morales, I., Alfaro, R., & Segovia, N. (2021). Indoor radon exposure and excess of lung cancer mortality: The case of Mexico—An ecological study. Environmental geochemistry and health, 43, 221-234.
- Prakash, R., Srinivasamoorthy, K., Gopinath, S., Saravanan, K., Vinnarasi, F., Ponnumani, G., ... & Anandhan, P. (2018). Radon isotope assessment of submarine groundwater discharge (SGD) in Coleroon River Estuary, Tamil Nadu, India. Journal of Radioanalytical and Nuclear Chemistry, 317, 25-36.
- Duggal, V., Sharma, S., Srivastava, A. K., & Mehra, R. (2018). Measurement of radon concentration in drinking water in Bhiwani district of Haryana. Journal of the Geological Society of India, 91, 700-703.
- Adyasari, D., Dimova, N. T., Dulai, H., Gilfedder, B. S., Cartwright, I., McKenzie, T., & Fuleky, P. (2023). Radon-222 as a groundwater discharge tracer to surface waters. Earth-Science Reviews, 104321.
- López-Abente, G., Núñez, O., Fernández-Navarro, P., Barros-Dios, J. M., Martín-Méndez, I., Bel-Lan, A., & Ruano-Ravina, A. (2018). Residential radon and cancer mortality in Galicia, Spain. Science of the Total Environment, 610, 1125-1132.
- Vogeltanz-Holm, N., & Schwartz, G. G. (2018). Radon and lung cancer: What does the public really know?. Journal of environmental radioactivity, 192, 26-31.

8. Meyer, W. (2019). Impact of constructional energy-saving measures on radon levels indoors. *Indoor Air*, 29(4), 680-685.
9. Symonds, P., Rees, D., Daraktchieva, Z., McColl, N., Bradley, J., Hamilton, I., & Davies, M. (2019). Home energy efficiency and radon: An observational study. *Indoor air*, 29(5), 854-864.
10. Noverques, A., Juste, B., Sancho, M., García-Fayos, B., & Verdú, G. (2020). Study of the influence of radon in water on radon levels in air in a closed location. *Radiation Physics and Chemistry*, 171, 108761.
11. Salthammer, T., Zhao, J., Schieweck, A., Uhde, E., Hussein, T., Antretter, F., & Birmili, W. (2022). A holistic modeling framework for estimating the influence of climate change on indoor air quality. *Indoor air*, 32(6), 13039.
12. Ruano-Ravina, A., Lema, L. V., Talavera, M. G., Gómez, M. G., Muñoz, S. G., Santiago-Pérez, M. I., & Perez-Rios, M. (2021). Lung cancer mortality attributable to residential radon exposure in Spain and its regions. *Environmental Research*, 199, 111372.
13. USEPA (1991) National primary drinking water regulations for radionuclides. US, Governmental Printing Office, Washington EPA/570/9-91/700.
14. Ground water information booklet Hassan district, Karnataka, central ground water board 2007.
15. Ground water information booklet Chikmagalur district, Karnataka, central ground water board 2007.
16. Stringer C, Burnett WC (2004) Sample bottle design improvements for radon emanation analysis of natural waters. *Health Phys* 87:642–646.
17. Raghavayya M, Iyengar MAR, Markose PM (1980) Estimation of Radium-226 by emanometry. *Bull Radiat Prot* 3:11–14 .
18. Vitz E (1991) Towards a standard method for determining waterborne radon. *Health Phys* 60:817–829.
19. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). (1993). Sources and effects of ionizing radiation. Report to the general assembly, with scientific annexes. United Nations sales publication Annex A, JOURNAL OF RADIATION RESEARCH AND APPLIED SCIENCES 25 Section III, Paragraph 133, Page No. 54. New York: United Nations.
20. US Environmental Protection Agency US EPA (1999) Radon in drinking water health risk reduction and cost analysis. *Fed Regist* 64:9559–9599.
21. WHO (World Health Organization). (2011). Guidelines for drinking water quality. Vol. 1. Recommendations (4th ed.). Geneva: World Health Organization
22. United Nations Scientific Committee on the Effects of Atomic Radiation UNSCER. (2008). Report of the United Nations scientific committee on the effects of atomic radiation. Fifty-sixth Session (10–18 July 2008) (No. 46). United Nations Publications.
23. Ravi, H. R., Sajan, C. P., Bapat, P. N., Madhukumar, D. M., Ghalib, W. A. M., & Mansoor, A. M. (2023). Determination of Radon Concentration in Groundwater of Areekode Region, Kerala, India—A Case Study. *Journal of the Geological Society of India*, 99(2), 281-286.
24. Al-Masri, M. S., & Blackburn, R. (1999). Radon-222 and related activities in surface waters of the English Lake District. *Applied radiation and isotopes*, 50(6), 1137-1143.