Indoor Radon Research conducted in South Africa from 1980s – To date (2019): A Review

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Abstract. The history of research on radon and indoor radon measurements in South Africa (SA) dates back to the mid-1980s and early 1990s. Small-scale studies have been performed in areas where high radon concentrations were expected due to the geology and the mining history of the area. Most of these studies were performed in Gauteng and Western Cape provinces. Gauteng province has a long history of gold mining and this has left behind large amounts of waste that contain long-lived naturally occurring radionuclides such as uranium-238 (^{238}U) which decays into radium-226 (^{226}Ra) from which radon-222 (^{222}Rn) emanates. Radon research conducted in the Western Cape Province was mainly due to the geology of this region, which is rich in granitic rocks. This study reviews published journal articles and reports on indoor radon measurement studies conducted across the country to establish a baseline data for the current study, which focuses on the development of a national radon survey and radon mapping strategy in SA. Moreover, findings made in this desktop review will inform the development of the national indoor radon database and the establishment of a regulatory framework for radon in dwellings and other buildings with high occupancy by members of the public.

KEYWORDS*: Radon progeny; Indoor Radon; NORM; Uranium, Mining impact; Regulatory Framework.*

1 INTRODUCTION

Radon-222 (^{222}Rn) is a naturally occurring, inert radioactive gas that is produced directly from the alpha decay of the long-lived) radium-226 (^{226}Ra) along the radioactive decay chain of uranium-238 (^{238}U). This radioactive gas is colourless and odourless, it cannot be detected by human physical sense and has a half-life of 3.82 days [1]. For many years it was believed that only underground mines have a high level of radon and mine workers are the only individuals that have significant radon exposure [2]. Many international studies have proven that occupants of above-ground workplaces and residences around gold or uranium mines and geological regions with high granitic content can also be exposed to high levels of radon that exceed the recommended levels [3].

Radon is by far one of the major contributors of radiation exposure to the public, including exposure in homes worldwide [4]. Inhalation or ingestion of radon progenies has proven to cause damage to the deoxyribonucleic acid (DNA) molecule of a cell and to induce lung cancer [5]. Reports by the International Agency for Research on Cancer (IARC) have confirmed that long-term exposure to radon and its short-lived decay products, polonium-218 (^{218}Po) and polonium-214 (^{214}Po) causes lung cancer in humans [3,6]. Studies on the health effects of radon in underground workplaces began several decades ago, the focus was extensively on uranium mineworkers. However, in the late 1970s and early 1980s, radon studies began to include measurements and surveys of radon gas concentration in private homes and other buildings with high occupancy factors for the public [7]. It is thus very important to conduct indoor radon measurements to assess the extent of human exposure to radon in dwellings and other public buildings with high occupancy by the public.

South Africa (SA) has a legacy of more than 100 years of gold mining; whereby gold along with uranium has been mined from the largest gold reefs of Witwatersrand since 1886. The Witwatersrand (Wits) Basin includes Central Rand Basin, Eastern Basin, Western Basin, Far West Basin, the Free State gold mines and the Klerksdorp goldfields comprising Klerksdorp, Orkney, Stilfontein, and Haartebeesfontein (KOSH) region. The 2019 analysis report of the Wits goldfields and the management of the consequent mine waste by Liefferink [8], reported that these mines have resulted in more than 270 tailings storage facilities (TSFs) with a uranium content of about 600 000 tones. As such, gold mine tailings are expected to have high levels of radon concentration since uranium, which is a long-term source of radon, is mined as a by-product of gold in South Africa [9, 10]. Moreover, these TSFs with high levels of uranium contain other toxic heavy metals associated with gold mining [11]. There have been many studies on the impact of gold mining in the country, however, indoor radon studies are still lacking. Therefore, there is a need for indoor radon survey and continuous monitoring in residential areas near gold and uranium mine tailings for the health assessment of community members living in such areas.

South Africa (SA) has never conducted a comprehensive national indoor radon survey and as a result, the country does not have an indoor radon map, which highlights possible radon hotspots like most international countries that are member states of the International Atomic Energy Agency (IAEA). Currently, SA does not have sufficient radon data and a regulatory framework for the protection of the public against the risk associated with radon. [12]. Thus, this paper reviews the currently available data on indoor radon in the country as part of the initial phases to the development of a South African indoor radon survey and mapping program. Findings made in this review serve as an indication of the possible challenges that exist in selected regions in the country mainly due to the geological formation and historical activities such as gold and uranium mining. Furthermore, observations made in this review will also inform the development of the national indoor radon database and the establishment of a regulatory framework for radon in dwellings and other buildings with high occupancy by members of the public like schools and kindergartens, offices and other aboveground workplaces. Overall, this review is a contribution to the long-term National Nuclear Regulator (NNR) plan to create a national database on indoor radon levels and the development of a national radon map.

2 METHODOLOGY

Information in this paper is based on the data collected from indoor studies conducted in SA since the 1980s to date (2019). Thus far, there has never been a nationwide indoor radon survey in SA. The available data that focuses on indoor radon measurements is from limited studies that have mostly been conducted by independent researchers for academic purposes and a few conducted by consultants for the then Atomic Energy Corporation (AEC), now South African Nuclear Energy Corporation (Necsa). Indoor radon concentration levels were obtained using different measurement techniques and devices, for varying measurement periods. No one method for indoor radon measurements has thus far been developed and applied in SA, therefore, this paper also reviews and discusses the different radon measurement techniques that were used and the results obtained.

3 TECHNIQUES AND DEVICES EMPLOYED IN THE REVIEWED STUDIES

Active or passive techniques are used for measurements of indoor, or both for verification purposes or determining the radon source. Currently, the market offers different types of instruments that are used for indoor radon measurements in both developed and developing countries. Radon tests can be conducted over short to long periods. Short-term measurements can vary from minutes, hours to a week, whereas long-term measurements can range from a minimum period of one month to a year. Punctual and continuous radon measurement techniques are short-term active methods, whilst integrated measurement techniques are long-term and passive. Outlined below are four of the radon measurement devices and techniques that have been used in various independent studies reviewed in this paper.

3.1 Solid State Nuclear Track Detectors (SSNTD)

Solid-state nuclear track detectors (SSNTD's) which are also referred to as "etched or alpha track detectors" are thin plastic sheets of different materials capable of recording alpha tracks. Because of their integral signal registration and insensitivity to low linear energy transfer (LET) radiations, they play an important role in radon passive integrated measurements. Track detectors exist in open and closed types and sampling is done in passive mode. The open SSNTD type can measure both radon and its decay products while the closed SSNTD type can only measure radon because it has a filter for radon progenies. This detector usually comes in two types, the LR115 (cellulose nitrate) and CR 39 (polyallyl diglycol carbonate) which is the most popular member of the detectors.

Alpha track detectors are used to measure the energy of alpha particles emitted by radon and its progenies (^{214}Po and ^{218}Po). A typical alpha energy spectrum of radon and its progenies have been reported energies of ^{222}Rn as 5.49 MeV, ^{218}Po as 6.02 MeV and that of ^{214}Po as 7.68 MeV [13]. When these heavily charged particles hit and pass through the SSNTD plastic film, the material undergoes ionization and localized damage is created on the molecular structure of the material. The damage caused on the detector is referred to as *latent tracks* [14]. The plastic material is etched in NaOH and KOH solution (ethanol can also be used) to visibly reveal latent tracks which are then viewed and counted under an optical microscope. To obtain representative data from buildings, the exposure period should be as long as possible [15, 16]. Generally, etched track detectors are deployed for a minimum period of a month to a maximum of one year, this differs per country.

3.2 Alpha GUARD Radon Monitors

The Alpha GUARD is one of the commonly used portable, real-time ionization chambers used for environmental radon measurements. It has the capability for measurement of radon in air, soil, water and building materials. This radon monitor has high storage capacity and can be battery or net-operated. It has an inbuilt rechargeable battery which can last for 10 to 15 days and this allows for operation independent of a power supply [17]. Due to its high sensitivity and long-time stable calibration, the Alpha GUARD is the reference instrument for professional radon monitoring and accurate measurement on site. It can be used for short as well as long-term radon measurements. In addition to the radon concentration in air, this device can simultaneously measure and record ambient temperature, relative humidity and atmospheric pressure with integrated sensors [18]. By combining the monitoring of radon with these associated environmental parameters it is possible to draw valid conclusions regarding the temporal and spatial distribution of the radon gas. This is of significant benefit initial radon screening and investigations during radon mitigation stage. These are continuous active radon detectors that contain an ionization chamber and uses alpha spectrometry for the detection of radon [19]. The device identifies the common radon isotopes (^{220}Rn and ^{222}Rn) by their different energies from the alpha decays. The generated signal from the detection of alpha particles is converted to a digital output. This output can be read on the Alpha GUARD, data saver or a computer [20].

3.3 Electret Ion Chambers EIC)

These passive devices are the electrostatic equivalent of permanent magnets, due to the permanent surface charge, the surface potential may be several kilovolts (kV). It functions as an interoperating detector for measuring the average indoor radon concentration during the measurement period [6]. It contains an electret which functions as a sensor in the ion chamber as well as a source of an electric field. A Teflon electret is placed at the bottom of a conducting plastic chamber called an electret ion chamber (EIC). Radon gas enters the chamber volume by passive diffusion through the inlet, this results in electret losing charge due to the general ionization of air produced by radon and its progenies in the chamber volume [15].

The positively charged electret at the bottom of the chamber collects the negative ions and the energy given off by the electret over a certain time interval is a measure of time integrated ionization during the interval. The energy given off by the electret in volts is measured by a noncontact battery-operated electret reader, this value in alliance with the calibration factor and the duration, are used to obtain the radon concentration. The EICs can be employed for short-term and long-term measurements. EICs designed for short term measurements can measure up to 15 days at a concentration of 50 Bq/m^3, and the long-term detectors are designed to measure from 3 to 12 months at a concentration of 150 Bq/m^3 [6]. These devices have proven to be a good measure of radon exposure; however, they have a limited dynamic range. They are sensitive to gamma rays, thus, compensation for this has to be applied. To obtain precise measurements, correction for the elevation must be made to compensate for the variation of atmospheric pressure effects [16].

3.4 Charcoal detectors

Activated charcoal devices are passive detectors that have a canister that holds granular-activated `1carbon and they do not require power [15]. These devices are used to measure indoor radon for 1-7 days [6, 21]. The charcoal absorbs the radon gas that gets into the canister through a screened opening, the absorbed radon will then decay and its progenies will be retained. After the set exposure period, the canister is sealed allowing the radon progeny gamma decay in the charcoal to be collected directly by the high purity germanium (HPGe) gamma spectrometry of the emissions from Lead-214 (^{214}Pb) and Bismuth-214 (^{214}Bi). Alternatively, it can be collected by liquid scintillation counting technique which uses 20 ml liquid scintillation vials that contain about 2-3 g of activated carbon [6]. The device is highly affected by humidity; therefore, it must be calibrated at different humidity levels. In high humidity the charcoal can become saturated, however, a diffusion barrier is used to reduce this humidity effects. The device must also be calibrated over the same duration of exposure and the temperature of the area it will be exposed at [6, 22]. The good thing about this method is that, since charcoal allows accumulation and desorption of radon, this method gives a very good estimation of the average of radon concentration over the exposure period if there's a small change in the radon concentration. Considering the half-life of ^{222}Rn which is 3.82 days, the device should be returned soon after the exposure period for analysis [22].

4 RESULTS AND DISCUSSION OF INDOOR RADON DATA FROM VARIOUS STUDIES IN SA

Table 1 presents the minimum and maximum range of the measurements that were obtained and the average concentration starting with the earliest available studies since 1980 to the latest study in 2019. The measurements were conducted indoors, in private dwellings and public buildings, most of the studies have limited or no data on specific procedures that were followed to obtain the results. The detector exposure periods followed in these studies also differed; they ranged from hours to months for both passive and active measurement devices. Specific characteristics of the buildings and habits of the inhabitants were not reported.

Table 4.1. Indoor radon concentrations from various studies conducted in SA from 1989-2019.

Region	**Location**	**Researchers**	**Year**	**Method of measurement**	**measurement period**	**Time and room measured in**	**Average concentration (Bq/m^3)**
Gauteng Western cape Gauteng	Witwatersrand Cape town Pretoria	A H Leuschner, D van As, Grundling, A Steyn [23].	1989	Track etch samplers and charcoal canisters	3 months Passive measurements	 Day time (average) Early morning	40 20 300 600
Western Cape	Paarl region near the Berg River (west) (East)	R. Lindsay, R.T. Newman, W.J. Speelman [26].	2008	Electret ion Chambers(E-PERM) (Passive technique)	5-20 days in the living room	Living room	132 37
North West province	Midvaal Water, Klerksdorp Botshabelo, Klerksdorp	Nnenesi A Kgabi [24].	2009	Radon Electret Chambers (S chamber, E-PERM type). (Passive technique)	25 days 21 days	Day time	30.16 ±2.52 pCi/L (1115.92 Bq/m^3) 46.06 ± 5.21 pCi/L (1704.220 Bq/m^3)
Western Cape Gauteng	Aardoom, Beaufort West Tshepisong, Soweto	NNR Position Paper (PP-0011), [27].	(n.d)	Electret ion Chambers (L – Chamber) Radon Gas Monitors (RGM)	443 days 28 – 30 days	Pantry & living room (n.a.)	478 211.9
Gauteng, Johannesburg	Ezulweni mine West Rand	Ava Nourian Dehkordi [19].	2011	Alpha Guard active detector RGMs Passive (SSNTND) technique	7 days 2 months	winter at night and early morning store-room, bedroom and living room	Winter 44.67; Summer 33.17 Winter 38.58; Summer 30.83 Average 38
Gauteng, Johannesburg	Carletonville	Kamunda C, Mathuthu M, Madhuku M [17].	2017	Alpha Guard Professional Radon Monitor (active technique)	24 hours over 3 days	(n.a.)	119.5
Gauteng, Johannesburg	Krugersdorp West rand region	Paballo Moshupya [31].	2017-2018	Solid-state nuclear track device (RGMs)	3 months	(n.a.)	105
Western Cape	Baviaansberg	Jacques Bezuidenhout [30].	2018	sodium iodide (NaI (Tl)) scintillation	5 minutes	Summer	400
Western Cape, Peninsula	Vredenburg Saldanha	R. R. Le Roux, J. Bezuidenhout, H. A. P. Smit [29].	2019	Electret ion chamber (Passive technique)	3 days	(n.a.)	58.7 38.6

4.1 Studies conducted: 1980 – 89:

Before the 1980s, there are no reported studies or existing data on indoor radon measurements in SA dwellings and public buildings such as offices, schools and similar types of workplaces. Table 2 below present summarized indoor radon data from the biggest study conducted by Leuschner and co-workers in 1988 - 1989. This study covered 2000 houses in 27 regions across the country. However, there was no information on the houses built around mine tailings. The highest indoor concentration was recorded at Paarl region in the Western Cape Province, the area is known to have a large number of granite rocks, which contain a high content of uranium. In 1989, the study was repeated at a house that recorded concentrations higher than 450 Bq/m^3 [2, 23]. The indoor radon concentration from all these regions was calculated to be 63 Bq/m^3 from measurements conducted during winter seasons of three consecutive years. Wooden floors and radium content in soil has also been reported to influence the high levels of indoor radon concentration. This was observed in a study done in the Witwatersrand region of Gauteng province, where high radon concentration levels were recorded in wooden floor houses compared to houses with other floor types. Measurements were taken from 100 houses and all the houses with wooden floor had concentrations higher than 80 Bq/m^3 [23]. In one house in Pretoria where measurements were taken in the basement, radon concentration levels of an excess amount of 1400 Bq/m^3 was recorded. This concentration was higher than the bedroom and living room concentration, however, measurements were also taken below the floor and the measured concentration was an excess amount of 1400 Bq/m^3 which was higher than concentrations in both the bedroom and living room [23].

Table 4.2. Summary of Indoor radon concentrations (Bq/m^3) from a study conducted in 1988-1989 **[23].**

Code and Town	Sample Size	Median	Geometric Mean	Average	Maximum
A Cape Town	134	10	9	13	52
B Bedfordview	16	23	20	20	72
C Malmesbury	59	25	24	42	150
D Richards Bay	76	33	26	38	120
E Rustenburg	10	34	31	33	48
F Parys	44	37	41	66	595
G Brits	30	38	35	42	119
H Paarl	60	39	45	85	842
I Johannesburg	284	45	37	49	197
J Stilfontein	72	45	50	62	131
K Sandton	16	46	46	50	106
L Roodepoort	6	50	49	61	130
M Akasia	7	52	51	57	97
N Soweto	150	54	53	56	131
O Hartbeespoort	28	56	49	59	145
P Boksburg	116	56	59	66	212
Q Verwoerdburg	29	57	55	61	136
R George	91	60	55	64	143
S Pretoria	148	61	54	66	197
T Phalaborwa	8	62	60	61	79
U Krugersdorp	53	65	67	77	273
V Springbok	67	70	60	78	340
W Beaufort–West	62	74	61	79	184
X Nababeep	88	78	79	87	393
Y Randfontein	45	80	84	92	185
Z Randburg	13	87	92	122	440
AA Germiston	143	93	89	116	297

4.2 Studies conducted: 1990 – 1999

Studies conducted in the period between 1990 – 1990 could not be found and some could not be accessed.

4.3 Studies conducted: 2000-2009

A study conducted by Kgabi and co-authors (2009) in the North West province around the Klerksdorp regions recorded an average of 30.16±2.52 pCi/L (1115.92 Bq/m^3) and 46.06±5.21 pCi/L (1704.22 Bq/m^3) in the Midvaal water and Botshabelo sites respectively [24]. Results in this study were compared to indoor radon concentrations from other southern African countries such as Swaziland, where a study by Mahlobo and co-workers (1995) showed that radon concentrations were higher in winter than in summer due to the ventilation system. The highest measured radon concentration in the Swaziland study was 87 Bq/m^3, which is lower than the concentration recorded in the in Klerksdorp study [25]. It was observed that radon concentrations build-up and exposure in Klerksdorp region was higher and probably the highest in the Southern African region. The variation of the indoor concentrations in the two regions were justified by the direction of the wind, which was determined in the two study sites. The wind direction values (2500° - 3600° from the North to West) were associated with high indoor radon concentrations in Botshabelo. It was further concluded that the wind blowing from the west and south-west in the Klerksdorp mining region elevates the exposure levels for the communities around Midvaal and Botshabelo. It was also concluded that the Klerksdorp gold mine region has the highest radon concentration, build-up and exposure in South Africa [24].

Other studies have also reported that the level of radium content in the soil that underlies the foundation of a building or house and the type of material used for floors can also influence the level of indoor radon concentration. In the Paarl region, measurements were taken from houses in the east and west side of the Berg River and Paarl mountain. Two-thirds of the houses in the west recorded concentration above 100 Bq/m^3 and these were all wooden floor houses. The main source of these high indoor radon concentration levels was reported to be due to the high level of radium in the soil [26].

The results presented in the NNR Position Paper PP-0011 showed that in Aardoom area in Beaufort West, the highest average radon concentration detected was 478 Bq/m^3. Radon measurements conducted in informal dwellings at Tshepisong in Soweto showed a range between 93.1 Bq/m^3 and 1728.5 Bq/m^3, with an average of 211.9 Bq/m^3. The concentration levels in this region were found to be associated with the Bird Reef Formation of the Witwatersrand Supergroup [27].

4.4 Studies conducted: 2010-2019

Studies have proven that granite rocks are the main source of elevated radon concentration levels [4, 28]. This is shown in a study conducted in the Vredenburg, Western Cape Province, where indoor radon concentration ranging between 190 Bq/m^3 and 200 Bq/m^3 with an average of 58.7 Bq/m^3 were recorded [29]. The study also reported that the other factor that contributed to these levels of indoor concentrations was the lifestyle of the occupants of the homes in the area. It was reported that the occupants live a ‘closed’ lifestyle, meaning there is limited airflow in their houses to diffuse indoor radon and minimize its build-up. Indoor radon concentration in Saldanha house located in an area with mild microclimate was calculated to be approximately 2.5 Bq/m^3. Residents in this house had an open lifestyle, meaning there is enough airflow to reduce the build-up of indoor radon. The low level of indoor concentration in this house confirms that the lifestyle of house occupants plays a role in the build-up of indoor radon.

Another factor that affects the indoor radon build-up and emanation is the type of building materials. In Saldanha,

the highest measured concentration of 86 Bq/m^3 was in a confined flat on the ground floor with few windows and a concrete ceiling. This house did not have enough airflow, resulting in high radon concentration [29]. In one of the studies where measurements were taken from the living room, bedroom and storeroom, the highest concentrations were measured during the winter season in the store-room using both the Alpha Guard (short-term) and the radon gas monitors (RGMs) (long-term measurements). The highest concentrations were 62 Bq/m^3 and 48 Bq/m^3 respectively. Since this house was the farthest from the slimes dam, it can be concluded that the recorded radon concentration was due to the lack of ventilation and the material used to build the house [19].
An excess indoor radon concentration of 400 Bq/m^3 was estimated through measurements of uranium concentration in the Western region, Saldanha Bay in Western Cape Province. The area is dominated by granite bedrock, which generally contains a high level of uranium. The presence of radon in this area was estimated by linking the measured uranium concentration to the indoor concentrations in Paarl since the two areas are geologically similar. The measured indoor radon concentration in the Paarl area was greater than 300 Bq/m^3 in about 6% of the houses. This confirms the predictions that 5.7% of the points would exceed 300 Bq/m^3 radon potential in Baviaansberg [30].

Recently, a study conducted by Moshupya and co-workers in 2018-2019 recorded indoor radon concentration levels with a maximum of 174 Bq/m^3 and an average of 105 Bq/m^3. This study was done in Kagiso Township in Krugersdorp, which is located west of Johannesburg city in Gauteng province. Johannesburg is the city which dominates the whole of SA with gold and uranium mines [28]. Solid-state nuclear track devices monitors (RGMs) with CR-39 polyallyl diglycol carbonate (PADC) which is highly sensitive to alpha particles were installed in dwellings to measure the levels of indoor radon. Outdoor radon measurements were also conducted in areas dominated by mine tailings and dams and the recorded radon concentrations levels ranged between 32 Bq/m^3 and 1069 Bq/m^3. The effective dose received by the public from outdoor exposure showed a maximum of 16 mSv/y, which is above the recommended level of 1 mSv/y proposed for public radiation exposure. This high levels of outdoor radon concentrations could be the source of indoor radon concentration [31].

Kamunda [32] also conducted a radon measurement study in Gauteng province, south-west of Johannesburg near the Carletonville mining area which also forms part of the renowned Witwatersrand basin. An alpha Guard Professional Radon Monitor was employed for indoor radon measurements. Indoor radon concentrations were measured overnight for about 24 hours in 6 houses in the east and west villages from the mine settlements and 2 houses from the control area. The average indoor radon concentration was 119.6 Bq/m^3 and the maximum value obtained was 472.0 Bq/m^3, which was said to be due to the high content of Uranium-238 in this region. The calculated annual effective doses ranged between 0.03 -11.89 mSv with an average value of 3.01 mSv, thus indicating a potential health hazard to the population residing in the area.

4.5 Indoor radon spatial map

Spatial distribution of indoor radon data obtained from studies conducted in various regions in South Africa is presented in Figure 1. It can be observed that there are areas with high indoor radon concentrations. It is also evident that there is limited data available on existing radon exposures indoors. The presented data indicate that it is important to conduct further investigations on a national scale to have a quantitative representation of existing radon exposure situations.

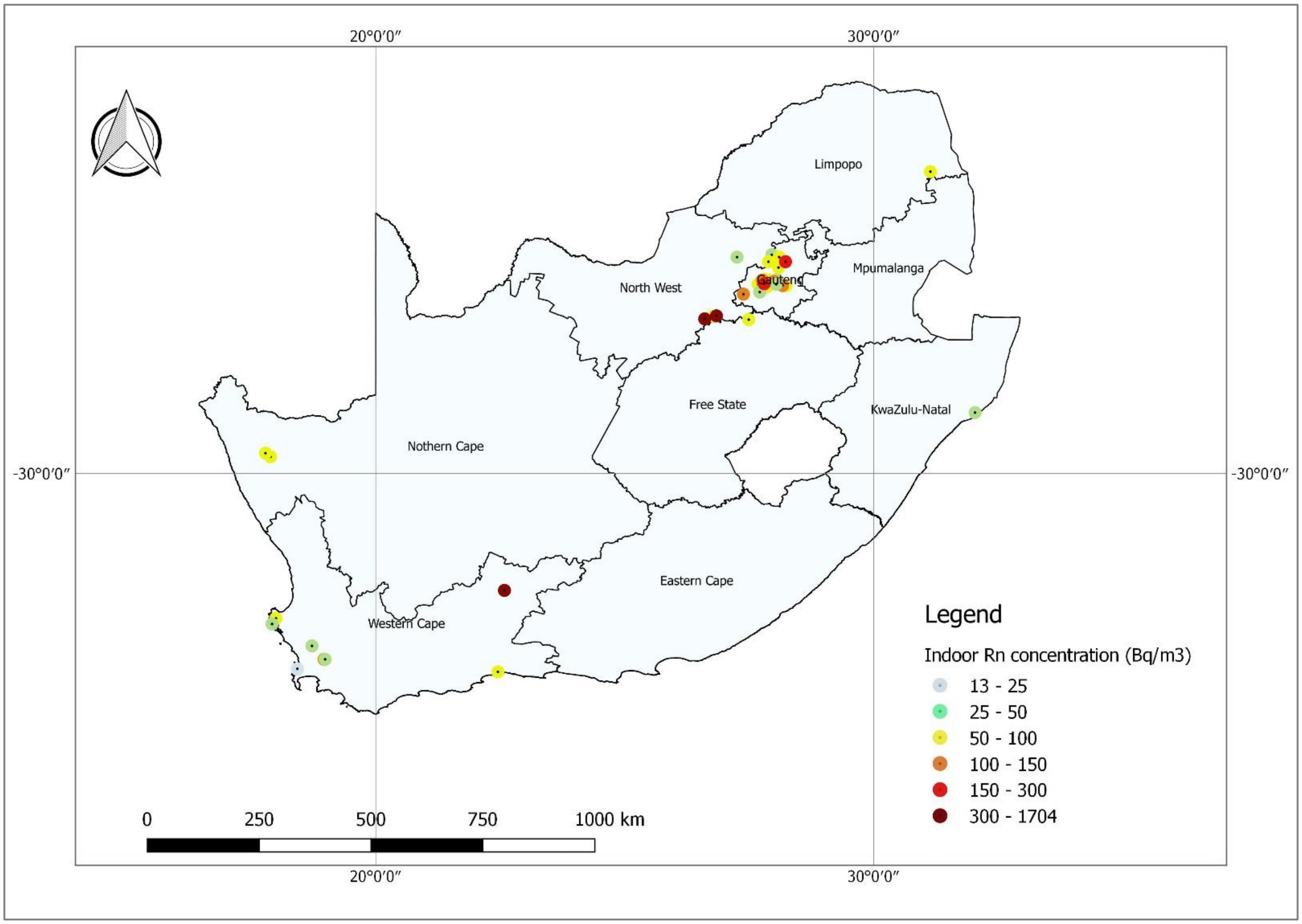

Figure 1: Indoor radon results obtained from various studies conducted in South Africa.

5 CONCLUSION

This paper reviewed the limited experimental studies and reports relating to indoor radon measurements in South Africa for the past four decades. The studies have revealed indoor radon concentrations vary due to factors such as geology (types of rocks), wind speed and direction, type of house, building material and floor type. Gold and uranium mine waste, mine tailings and granite rocks with high uranium content were found to be major sources of indoor radon in most of the conducted studies. The possible entry mechanism of radon in dwellings near mine tailings is due to the infiltration of radon bearing air released from tailings and soil that contain a high concentration of ^{226}Ra leached from tailings. It is observed from the studies conducted in the Paarl region in the Western Cape and the Witwatersrand in the Gauteng Province, that floor type influences indoor radon concentration levels. These studies reported elevated indoor radon concentrations in homes that had wooden floors compared to houses with other floors types.

Currently, the available data only serves as an indication that there might be an indoor radon challenge in the country, especially in regions with a history of gold mining activities and areas that have a geological formation with high uranium or granitic content. It is thus necessary for SA to conduct an indoor national radon survey and radon map, this will help with the identification of possible radon hotspots and public exposure areas. Moreover, this will enable the development of policies and building codes to prohibit development of radon hotspots into residential areas. Radon mapping will increase awareness about the health hazards of exposure to radon over a long period.

One of the objectives of this paper was to find a trend in the studies reviewed. From the data presented in Table 1 and Figure 1, there is still a wide data gap that needs to be filled by further research and integrated, long-term indoor radon measurements to collect quality data especially in potential radon hotspots such as residential areas around the gold or uranium mining areas and mine dumps. With sufficient data, it will be possible to establish a trend between parameters that influence indoor radon accumulation as well as the development of a national radon database, and ultimately a national radon map. Moreover, this will assist in determining the sources of indoor radon in different regions and further guide in future epidemiological and environmental impacts studies. From this review paper, it is concluded that further research and data collection is required to inform the development of regulation o manage conditions in existing exposure situations.

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