GEOGENIC RADON AND THORON POTENTIAL MAPPING IN JOHOR STATE, MALAYSIA

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Science
Universiti Teknologi Malaysia

MARCH 2021

DEDICATION

This thesis is dedicated to my late father Alhaji Haruna Makarfi, who would have given me all the required support if alive, my mother Hajiya Mairo Ibrahim Makarfi for her tireless prayers and support all through my life. And my dearest son Haruna Adamu Dada for enduring my absence while I am away from him during this study.

ACKNOWLEDGEMENT

My sincere gratitude to Allah (SWT), whose help and guidance took me through this programme. May the benediction, blessings and peace of Allah (SWT) be with His noble servant, prophet and messenger Muhammad (SAW), members of his household and his companions, amin.

I would like to express my profound gratitude and appreciation to my supervisors, Associate Prof. Dr. Muneer Aziz Saleh, Associate Prof. Suhairul bin Hashim, Associate Prof. Khaidzir Bin Hamzah and Dr. Mohamad Syazwan Mohd Sanusi, who have infused a sense of style, soft approach, kind mentorship, and invaluable contributions to the success and quality of this work.

My appreciation also goes to my research colleagues, Habila Nuhu and Nur Fadhilla Bint Ismail. Am thankful to the staff of Nuclear Laboratory, Department of Physics, Universiti Teknologi Malaysia especially Mr Saiful Bin Rashid and Nuclear physics laboratory of University Industry research laboratory.

My sincere gratitude goes to the management of Federal College of Education, Zaria, Nigeria for providing financial support through Tertiary Education Trust Fund (TETFUND) for my study.

Special gratitude and appreciation go to my mother and her entire family members especially my uncle Aliyu Ibrahim Makarfi for their support, encouragement and above all prayers. The same goes to my brother-inlaw Professor Lawal Saidu Makarfi, my siblings (Aunty Zainab, Aliyu Ibrahim, Musa Ibrahim, Hauwa Haruna, Ibrahim Haruna, Aliyu Haruna, Sulaiman Haruna and Maimuna Haruna), and friends Hajara Musa, Ahmad Umar Ahmad, Dr. Jibrin Muazu Musa and many others for their tireless unreserved support, care and love towards the success of my study.

My fellow postgraduate student should also be recognized for their support. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family members.

ABSTRACT

Public radiation exposure to natural ionizing radiation is due to radon and its progeny. Knowledge of natural radioactivity exposure level is significant for making policy regarding radiological protection of the environment and humans. This study aims at establishing baseline data and identifying areas with the probability of high radon (^{222}Rn/^{220}Rn) exposure in Johor State, Malaysia. Therefore, The RAD7 alpha detector coupled to air sampling accessories, soil gas probe and RAD-H_2O was used to measure the activity concentrations of ^{222}Rn/^{220}Rn in outdoor air, ^{222}Rn /^{220}Rn in soil gas and ^{222}Rn in water, respectively. The RAD7 recorded the average temperature and relative humidity during measurement of ^{222}Rn/^{220}Rn in soil gas. The data for soil gas permeability was obtained with RADON-Joke equipment. The terrestrial gamma dose rate was measured using a portable NaI (Tl) survey meter. The specific activity of ^{226}Ra, ^{232}Th, and ^{40}K in the soil samples was determined using a high purity germanium detector (HPGe). The established data range from minimum detectable activity (MDA) to 127.25 ± 3.00 Bq L^{-1} for ^{222}Rn and MDA to 159.07 ± 3.40 Bq L^{-1} for ^{220}Rn in soil gas, respectively. The data for ^{222}Rn and ^{220}Rn in outdoor air range from MDA to 3850 ± 180 mBq L^{-1} and MDA to 600 ± 17 mBq L^{-1}, respectively. The measured data categorized according to the study area's geological formations show that higher values of ^{222}Rn /^{220}Rn in both soil gas and outdoor air were obtained in regions underlain with Triassic and Intrusive rock geological formations. The soil gas permeability data has a mean value of 1.9×10^{-12} m^2. The field data obtained from the measurement of ^{222}Rn in soil gas and soil gas permeability were used to estimate the geogenic radon potential (GRP) of this study area. Three high categories of GRP values were identified (53.667, 53.252 and 47.826). Statistical correlation analysis indicates that the estimated GRP data is strongly correlated with the measured ^{222}Rn/^{220}Rn in soil gas and soil gas permeability. In contrast, an insignificant relationship was obtained between the measured ^{222}Rn/^{220}Rn in soil gas and the measured ^{226}Ra/^{232}Th in the surface soil. The recorded relative humidity was found to have a moderately negative correlation with ^{222}Rn in soil gas. The measured data of ^{222}Rn activity concentrations in water varies from 80 ± 110 to 5400 ± 1100 mBq L^{-1} in surface water and spring water source, respectively, with a mean value of 1227 mBq L^{-1} from all samples. The water samples measured activity concentration was found to be below the maximum permissible limit for ^{222}Rn in water referring to United States Environmental Protection Agency (EPA) and World Health Organisation which is 1100 mBq L^{-1} and 10^5 mBq L^{-1}, respectively. The mean activity concentration of ^{222}Rn in spring water is five times higher than that of surface water. The mean values of the annual effective dose due to inhalation of ^{222}Rn in spring water and surface water, were 2.15 µSv y^{-1} and 0.423 µSv y^{-1}, respectively. Hence, the inhalation doses estimated were well below the recommended limit set by United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) of 1260 µSv y^{-1}. The maps of spatial distribution of ^{222}Rn/^{220}Rn in soil gas and soil gas permeability are created and indicates that higher values of ^{222}Rn and ^{220}Rn were obtained from Ledang, Muar and Johor Bahru districts.

ABSTRAK

Pendedahan sinaran orang awam terhadap sinaran mengion semula jadi adalah disebabkan oleh radon dan progeninya. Pengetahuan mengenai tahap dedahan keradioaktifan semula jadi adalah penting untuk membuat dasar berkaitan perlindungan radiologi terhadap alam sekitar dan manusia. Kajian ini bertujuan untuk menetapkan data asas dan mengenal pasti kawasan dengan kebarangkalian dedahan radon (^{222}Rn / ^{220}Rn) yang tinggi di negeri Johor, Malaysia. Oleh itu, pengesan alfa RAD7 yang digabungkan dengan aksesori pensampelan udara, kuar gas tanah dan RAD-H_2O masing-masing digunakan untuk mengukur kepekatan aktiviti ^{222}Rn /^{220}Rn di udara luar, ^{222}Rn / ^{220}Rn di dalam gas tanah dan ^{222}Rn di dalam air. RAD7 mencatatkan suhu purata dan kelembapan relatif semasa pengukuran ^{222}Rn / ^{220}Rn di dalam gas tanah. Data untuk kebolehtelapan gas tanah diperoleh dengan peralatan RADON-Joke. Kadar dos gama daratan diukur menggunakan meter tinjau NaI (Tl) mudah alih. Keaktifan tertentu untuk ^{226}Ra, ^{232}Th, dan ^{40}K di dalam sampel tanah ditentukan menggunakan pengesan germanium ketulenan tinggi (HPGe). Julat data yang diperoleh masing-masing bermula dari keaktifan minimum boleh kesan (MDA) sehingga 127.25 ± 3.00 Bq L^{-1} untuk ^{222}Rn dan MDA sehingga 159.07 ± 3.40 Bq L^{-1} untuk ^{220}Rn dalam gas tanah. Data untuk ^{222}Rn dan ^{220}Rn di udara luar berjulat dari MDA sehingga 3850 ± 180 mBq L^{-1} dan MDA sehingga 600 ± 17 mBq L^{-1}. Data yang diukur dikategorikan menurut bentukan geologi kawasan kajian ini menunjukkan bahawa nilai ^{222}Rn / ^{220}Rn yang lebih tinggi di kedua-dua gas tanah dan udara luar diperolehi di kawasan teralas dengan bentukan geologi Trias dan Batuan Rejahan. Data kebolehtelapan gas tanah mempunyai nilai min 1.9×10^{-12} m^2. Data lapangan yang diperoleh dari pengukuran ^{222}Rn dalam gas tanah dan kebolehtelapan gas tanah digunakan untuk menganggar potensi radon geogenik (GRP) kawasan kajian ini. Tiga kategori nilai GRP yang tinggi telah dikenal pasti (53.667, 53.252 dan 47.826). Analisis korelasi statistik menunjukkan bahawa anggaran data GRP sangat berkorelasi dengan ^{222}Rn/^{220}Rn yang diukur di dalam gas tanah dan kebolehtelapan gas tanah. Sebaliknya, hubungan yang tidak signifikan diperoleh di antara ^{222}Rn /^{220}Rn yang diukur dalam gas tanah dan ^{226}Ra/^{232}Th yang diukur di permukaan tanah. Kelembapan relatif yang direkodkan didapati mempunyai korelasi negatif yang sederhana dengan ^{222}Rn dalam gas tanah. Kepekatan keaktifan ^{222}Rn yang diukur di dalam air berubah masing-masing dari 80 ± 110 sehingga 5400 ± 1100 mBq L^{-1} di permukaan air dan sumber mata air, dengan nilai min 1227 mBq L^{-1} dari semua sampel. Kepekatan keaktifan sampel air yang diukur didapati berada di bawah had maksimum yang dibenarkan untuk ^{222}Rn dalam air merujuk kepada Agensi Perlindungan Alam Sekitar Amerika Syarikat (EPA) dan Pertubuhan Kesihatan Sedunia, yang masing-masing adalah 1100 mBq L^{-1} dan 10^{5} mBq L^{-1}. Min kepekatan keaktifan ^{222}Rn dalam mata air adalah lima kali lebih tinggi daripada permukaan air. Nilai min dos berkesan tahunan disebabkan oleh penyedutan ^{222}Rn di dalam mata air dan permukaan air masing-masing adalah 2.15 µSv y^{-1} dan 0.423 µSv y^{-1}. Oleh itu, dos penyedutan yang dianggarkan berada jauh di bawah had yang disyorkan oleh Jawatankuasa Saintifik Pertubuhan Bangsa-Bangsa Bersatu mengenai Kesan Sinaran Atom (UNSCEAR) iaitu 1260 µSv y^{-1}. Peta taburan ruangan ^{222}Rn/^{220}Rn di dalam gas tanah dan kebolehtelapan gas tanah dihasilkan dan menunjukkan bahawa nilai ^{222}Rn dan ^{220}Rn yang lebih tinggi diperoleh dari daerah Ledang, Muar dan Johor Bahru.

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LIST OF ABBREVIATIONS

FWHM	Full width Half Maximum
GRP	Geogenic Radon Potential
HPGe	High Purity Germanium Detector
ICRP	International Commission on Radiological Protection
IDW	Inverse Distance Weighting
SPSS	Statistical Package for Social Sciences
UNSCEAR	United Nations Scientific Committee on the effect of Atomic Radiation
WGS	World Geodic Coordinate System
WHO	World Health Organization

LIST OF SYMBOLS

^{220}Rn	Thoron
^{222}Rn	Radon
^{226}Ra	Radium-226
^{232}Th	Thorium-232
^{238}U	Uranium-238
^{40}K	Potassium-40
Bq	Becquerel
cpm	Count per minutes
cps	Count per second
DCF	Dose conversion factor
D_{Einh}	Effective dose for inhalation
E_f	Equilibrium factor
$E\gamma$	Energy of the gamma-ray
N	Number of radionuclide at time t
N_0	Number of radionuclide time at $t = 0$
N_{sam}	Net count of the radionuclide in the sample
P_E	Gamma-ray emission probability (gamma yield)
R_{aW}	Ratio of ^{222}Rn in the air to ^{222}Rn in water
$t_{1/2}$	Half-life
T_o	The average occupancy time per individual
ε	Efficiency of a detector
λ	Radioactive decay constant

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CHAPTER 1

INTRODUCTION

1.1 Background of the study

Radon is a naturally occurring radioactive gas that can be found everywhere in our environment. It is chemically inert; it's odour can neither be seen nor perceived in the environment. It has several isotopes, but the isotopes of interest for this study are ^{222}Rn (radon) and ^{220}Rn (thoron) due to their availability in the environment and adverse health impacts on human (WHO, 2009). ^{222}Rn with a half-life of 3.82 days belongs to the natural decay series of uranium-238 (^{238}U) with a half-life of 4.47×10^{9} y. Thoron (^{220}Rn), with a half-life of 55.6 s belongs to the natural decay series of thorium-232 (^{232}Th) of 14.1×10^{10} y half-life. The parent nuclide of ^{222}Rn (^{238}U) originates from uranium ores, igneous and metamorphic rocks such as granite, gneiss, shale, phosphate rock and schist. It can also be found in a small amount in common rocks such as limestone (Kusky, 2005). The parent nuclide of ^{220}Rn (^{232}Th) originates from various types of rocks: veins of thorite, thorianite, monazite in granites, syenites-pegmatites and other acidic intrusions. It is also present in monazite in quartz-pebble conglomerates, sandstones, fluviatile, and beach placers (Ramachandran, 2010). These natural radioactive gases transfer from their origin by diffusion and for longer distances by advection dissolving either in water or carrier gases, before finally blowing out into the atmosphere. Their discharge mainly depends on ^{226}Ra and ^{232}Th content and mineral grain size, geophysical and geochemical parameters that ruled their transport in the earth, and the hydrometeorological environments (Etiope *et al.*, 2002).

The most stable isotope of radon is ^{222}R, which decays to short-lived daughters (^{218}Po and ^{214}Po), contributing to the maximum risk associated with radon exposure by inhalation in general. When ^{222}Rn and ^{220}Rn isotopes set down in the lungs, the emitted alpha radiation from them can affect the lung's tissue. ^{222}Rn exposure accounts for more than 50% of the lifetime radiological dose to a person, while ^{220}Rn contribution is about ten times smaller than ^{222}Rn (Li *et al.*, 2010). However, some studies revealed that in some circumstances, doses from ^{220}Rn and its decay products can be analogous to those from ^{222}Rn and its decay products, or even larger (Cinelli *et al.*, 2015; Khokhar *et al.*, 2008; Porstendorfer, 1994; Steinhzlusler, 1996). The link between radon exposure and lung cancer is well-established (Yamada *et al.*, 2006; Brauner *et al.*, 2012; Sethi *et al.*, 2012; Zhang *et al.*, 2012). Studies in Asia, Europe and North America provide convincing proof that a significant number of lung cancers were caused by indoor radon exposure. Recent estimates of the number of lung cancers due to radon range from 3 to 14%, subject to the calculation method employed and the mean radon concentration in the country concerned. The analysis show that the risk of lung cancer is directly proportional to radon exposure. Majority of the lung cancers related to radon were due to exposure to low and moderate radon concentrations rather than higher radon concentrations. (WHO, 2009).

Previous studies have revealed the soil gas permeability, which is closely related to the migration of radon gas, determine the rate at which radon escape to the atmosphere (Andersen, 1999; Alonso *et al.*, 2019). The grain size and porosity of a given terrain greatly influence the soil permeability, which increases with the existence of structural discontinuity and karst phenomena. The derived radon flux can fluctuate significantly with soil gas's permeability; hence, the soil gas's ^{222}Rn activity concentration also varies. The soil gas permeability is greatly affected by soil wetness, which at once is influenced by other factors like phreatic level and pluviometry variations (Alonso *et al.*, 2019). A sharp decrease in the ^{222}Rn activity concentration in soil gas can be found as the amount of water in soil rises and advances towards saturation level due to the sudden reduction in the soil gas permeability level (Alonso *et al.*, 2019; Menetrez et al., 1997). The occurrence of an apparent low permeable soil layer indicates a rise in the accumulation of ^{222}Rn below (Alonso et al., 2019; Johner and Surbeck, 2001). It may as well lead to a significant reduction in the soil-atmosphere ^{222}Rn flux. The reduction of soil-atmosphere radon flux can arise due to diverse reasons, such as water composition near the saturation level or the natural origin of the material if soil comprises clay and blacktop (Alonso *et al.*, 2019; Wiegand 2001).

The harmful health impact of ^{222}Rn is well documented. Therefore, it has been considered necessary to know the geographical extent of the hazard (radon risk) associated with it, for regulation and alleviation purposes. The term 'radon risk' is defined as the natural cause of the hazard over a given geographical location (Szabó *et al.*, 2014). To prevent radon exposure to the public, numerous nations have addressed identifying regions most at risk of ^{222}Rn exposure by establishing diverse ^{222}Rn mapping techniques. The created maps are valuable in understanding and interpreting the spatial variation of ^{222}Rn in a given location and serve as a predictive tool when planning housing developments. The map can also help identify areas with dwellings that are likely to be at high risk of ^{222}Rn exposure (ICRP, 1993; Kemski *et al.*, 2001; Kemski *et al.*, 2009). The radon-risk mapping was previously done by extensive indoor radon measurement (Miles, 1998; Andersen, 1999). However, indoor measurement requires a large number of measurements over a long time. Also, indoor radon measurement considers the complex function of numerous factors, for instance, the geological nature of the area, building materials, presence and type of basement or cellar underneath the house and lifestyles of the inhabitant of a given dwelling. Methods such as airborne gamma-ray spectrometry in combination with geological data were also used (Appleton *et al.*, 2011; Ford *et al.*, 2001; Smethurst *et al.*, 2008). Evaluation of gamma dose based on the correlation of ^{222}Rn level in the soil gas with ^{238}U or ^{226}Ra level in soils and rocks has also been implemented (Ielsch *et al.*, 2010; García-Talavera *et al.*, 2013a). However, the primary sources of ^{222}Rn and ^{220}Rn in houses are soil and underlying bedrocks upon which houses are built. The rate of emission from these sources and the potential for concentration within houses vary considerably with location. ^{222}Rn in the soil air was considered a good predictor of a given site's radon potential. (Nazaroff *et al.*, 1988; Mose *et al.*, 1992; Kardos *et al.*, 2015). In practice, radon exhalation's direct measurement towards indoor air seems to be best in characterizing a given site's radon potential. However, direct measurement of this factor requires prolonged intervals. Therefore, a combined measurement of ^{222}Rn activity concentration in soil gas and soil gas permeability has been considered a superior standard in mapping radon risk region (Kemski et al., 2001; Neznal et al., 2004).

^{222}Rn is soluble in water and therefore exist in the waters that pass through soils and rocks of uranium and thorium content. The dissolved ^{222}Rn in water mainly originate from ^{226}Ra that either dissolve in water or localized in a porous and permeable rock aquifer or soil materials in contact with water. When ^{222}Rn atoms are produced in soil or rocks, they have the potency to be expelled from the soil grain by alpha-recoil and transported to groundwater or void air and seep through the atmosphere (Abdallah *et al.,* 2007; Somlai *et al.,* 2007; Tabar and Yakut, 2014; Marques *et al.*, 2004). Numerous studies were conducted to investigate the relationship between ^{222}Rn activity concentration in water and the geological environment. Elevated ^{222}Rn levels are commonly found in the ground and spring waters discharging from metamorphic and granitic rocks (Michel, 1990; Durrani, 1999; Weise *et al.*, 2001; Aleissa *et al.*, 2012; Freiler *et al.*, 2016). Moreno et al. (2014) reported that Felsic granites contain an excessive concentration of the parent element of the ^{222}Rn decay series (^{238}U). Most of the spring waters in Johor State are found in the region of intrusive rocks of granitic origin (Director-General of Geological Survey Malaysia, 1985). The associated hazard of ^{222}Rn ingestion is less than that of inhalation of ^{222}Rn that exhale into the air from the same water (Crawford-Brown, 1990; DURRIDGE Company Inc., 2011; Duggal *et al.*, 2020). Therefore, it is considered necessary to quantify ^{222}Rn in water and evaluate the associated doses of inhalation due to ^{222}Rn in water to ensure the dwellers' safety near the waters.

The level of ^{222}Rn in the outdoor air is generally low and poses no problem, ranging from 0.005 to 0.015 Bq L^{-1} (WHO, 2016). However, radon in the outdoor air may also contribute to indoor radon levels, as in some geographical locations, outdoor radon levels are higher than indoors (Vaupotič *et al.*, 2010). Therefore, assessment of radon in the outdoor air is also necessary.

Since both ^{222}Rn and ^{220}Rn are ubiquitous and presents a significant health hazard to the populace, there is a need to identify areas with possible high exposure for radiological assessment and establishment of national policy concerning their exposure. Therefore, this research hopes to establish baseline data and identify those areas with high ^{222}Rn and ^{220}Rn exposure probability. This finding may be useful in setting a safety standard for exposure to ^{222}Rn and ^{220}Rn in Malaysia's Johor state.

1.2 **Problem Statement**

Despite the significant radiation dose contributed by ^{222}Rn in the environment (more than 50 % of natural radiation dose), baseline data for ^{222}Rn and ^{220}Rn activity concentration in the Johor State has not been established. Therefore to identify areas most at risk of ^{222}Rn and ^{220}Rn exposure in Johor state, a baseline data is needed for both ^{222}Rn and ^{220}Rn activity concentration as doses from ^{220}Rn exposure can be analogues to that of ^{222}Rn or even higher (Cinelli *et al.*, 2015; Khokhar *et al.*, 2008; Porstendorfer, 1994; Steinhzlusler, 1996). Therefore, exposure to ^{222}Rn and ^{220}Rn cannot be considered safe no matter the amount as prolonged exposure to lower doses has been associated to the occurrence of lung cancer (WHO, 2009; Dubois *et al.*, 2010). Moreover, lung cancer is considered the leading cause of cancer-related deaths worldwide (Lee *et al.*, 2011; Sethi *et al.*, 2012).

Most of the previous studies conducted in the Johor State were concerned with assessing natural radionuclides in the surface soil and terrestrial gamma dose, For example, (Ramli *et al.*, 2005; Saleh *et al.*, 2014, 2013a, 2013b, 2013c). However, in identifying the radon risk region, studies on natural radionuclide in the surface soil cannot provide adequate information about a given area's radon risk. The concentration of ^{222}Rn/^{220}Rn depends on several factors, other than the concentration of their parent nuclides, among which soil gas permeability is considered the most significant factor (Alonso *et al.*, 2019). Therefore, to assess an area's radon risk, a combined measurement of soil gas radon and soil gas permeability needs to be conducted (Neznal *et al.*, 2004).

Based on the map of the geological survey of Peninsular Malaysia (Director-General of Geological Survey Malaysia, 1985) most of the spring waters in Johor State are outflowing from granitic rock aquifers. The rock aquifers of granitic type have been associated with a high concentration of ^{222}Rn precursors (Michel, 1990; Durrani, 1999; Weise *et al.*, 2001; Aleissa *et al.*, 2012; Freiler *et al.*, 2016). These spring waters serve as recreational centres and the origin for most surface waters (WWF Malaysia, 2011). Although the harmful effect of ^{222}Rn exposure is well established, a ^{222}Rn data on this natural and useful water source of Johor State has not been found in the literature.

1.3 Objectives of the study

This research aims at identifying the radon risk areas in Johor State Malaysia using the measurement of ^{222}Rn in soil gas and soil gas permeability. The objectives of the study are:

(a) To establish a baseline data on ^{222}Rn and ^{220}Rn activity concentrations in soil gas, ^{222}Rn and ^{220}Rn activity concentrations in outdoor air and soil permeability for Johor State Malaysia.

(b) To estimate the geogenic radon potential data and establish the radon potential map of Johor State.

(c) To classify radon and thoron based on the geological formations and the soil types of Johor State.

(d) To find the statistical relationship between the estimated data of the geogenic radon potential and other measured parameters (^{222}Rn in soil gas, ^{220}Rn in soil gas, ^{222}Rn in outdoor air, ^{220}Rn in outdoor air, soil gas permeability, ^{226}Ra in soil, ^{232}Th in soil, and gamma dose rate, respectively).

(e) To measure the activity concentrations of ^{222}Rn in spring, lake and river waters and estimate the effective dose due to ^{222}Rn inhalation.

1.4 Scopes of the Research

This research was conducted in Johor State Malaysia, covering six geological formations, seven soil types, and ten administrative districts within Johor State.

The study focused on in situ measurements of ^{222}Rn and ^{220}Rn activity concentration, outdoor air, soil gas, and soil gas permeability. The internal temperature and relative humidity of RAD7, during measurements of ^{222}Rn/^{220}Rn in soil gas and ^{222}Rn/^{220}Rn in outdoor air, were recorded. Measurements of ^{222}Rn activity concentration in water samples and terrestrial gamma dose rate measurement at 1 m from the soil surface were also conducted. Soil samples were collected from 111 sampling points for determination of the specific activity of ^{226}Ra, ^{235}Th and ^{40}K in the laboratory. The geographical coordinates of each sampling locations were also recorded.

The geogenic radon potential (GRP) and the effective dose of inhalation due to ^{222}Rn in water were estimated. Kruskal-Wallis test was conducted to verify any significant differences among the soil types and geological formations on the measured data for ^{222}Rn in soil gas, ^{220}Rn in soil gas and the estimated GRP data.

The estimated GRP data other measured parameters (^{222}Rn/^{220}Rn in soil gas ^{222}Rn/^{220}Rn in outdoor air, soil gas permeability, the specific activity of ^{226}Ra, ^{235}Th And ^{40}K in the soil and terrestrial gamma dose) were subjected to Spearman's correlation test to estimate the statistical relationship among the measured data sets.

Spatial interpolation of the measured data for ^{222}Rn/^{220}Rn soil gas, GRP, and soil gas permeability was done to obtain a map of each data set's spatial distribution.

1.5 Significance of the Research

This research work aims to delineate the radon (^{222}Rn/^{220}Rn) risk areas in Johor State and produce maps that can help identify those areas above the internationally acceptable level. Identifying regions most at risk of radon exposure serves as a key to policy on environmental carcinogen control (García-Talavera *et al.*, 2013). A map of radon-prone areas will provide management instruments for helping establishments take appropriate decisions and target actions in priority areas, such as building regulations to prevent new structures with high radon levels (Demoury *et al.*, 2013). Therefore, this study's findings will be very significant to environmental protection agencies, radiological protection agencies, and the populace in the

Johor state. This is because geographical-based, radon surveys estimate the distribution of radon in various areas. Also, the radon potential map established can be valuable data in executing radon policy. It can be useful in optimizing the search for high radon concentrations and identifying areas that require individual preventive actions during new construction (WHO, 2009).

1.6 **Theses Outline**

The thesis consists of five chapters arranged in chronological order. The first chapter provides the background of the research work, statement of the problem, aims, and objectives of the research, significance of the study and scope of the study.

Chapter 2 contains a relevant literature review on; radioactivity, types of radiation, radioactivity in the environment, radioactive decay law, and radioactive equilibrium. The chapter also presents studies on ^{222}Rn and ^{220}Rn activity concentrations in the soil gas, ^{222}Rn and activity concentrations in water, done in different countries and Malaysia.

Chapter 3 describes the study area as well as the methodology adopted to achieve the stated objectives. It includes measurements of, ^{222}Rn and ^{220}Rn in air, ^{222}Rn and ^{220}Rn in soil gas and ^{222}Rn in water with Durridge RAD7 alpha particle detector, together with in situ gamma dose-rate measurement, soil permeability measurement, geographical coordinate measurement, and soil sample collection and preparation for gamma spectroscopy with HPGe. The chapter also comprises equations to evaluate the radiological health hazards and the study location's geogenic radon potential.

Chapter 4 presents the summary statistics of all the measured parameters (^{222}Rn/^{220}Rn in soil gas, ^{222}Rn/^{220}Rn in outdoor air, soil gas permeability, estimated GRP data, relative humidity, and the recorded temperature). The chapter also presents the distribution and discussion of the measured parameter based on Administrative Districts, geological formations, and soil types. The result of the correlation between the measured parameter is also presented and discussed. The statistical summary and discussion of the measured ^{222}Rn in water with the estimated inhalation dose are also presented. Maps that show the spatial distribution of the measured ^{222}Rn in soil gas ^{220}Rn in soil gas, soil gas permeability, and the geogenic radon potential are displayed in this chapter.

Chapter 5 presents the conclusion drawn from this study as well as the recommendations.

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2. Haruna, R., Saleh, M. A., Hashim S., Hamzah, K., Zainal, J., Rusli, N., Sanusi, M.S.M. (2020b). The Geogenic Influences on ^{220}Rn Activity Concentration in Soil Gas of Johor State, Malaysia. Environmental Earth Sciences, https://doi.org/10.1007/s12665-21-09413-z.

3. Haruna, R., Saleh, M. A., Hashim S., (2020). Preliminary Investigation of Radon Activity Concentration in Outdoor air of Johor, Malaysia. 4Th Asian International Multidisciplinary Conference (AIMC 2020).