GEOGENIC MAPPING OF RADON AND THORON CONCENTRATION IN PERAK STATE MALAYSIA

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ABSTRACT

Radon and its daughter isotopes exist in the natural environment and can significantly contribute to human exposure to ionizing radiation. Knowing an environment's radon levels can help the radiological protection agencies in policymaking. This research seeks to quantify the activity of radon (^{222}Rn) and thoron (^{220}Rn), and their mapping, to identify risk areas in Perak state, Malaysia. The RAD7 detector coupled to soil probe, air sampling, and RAD-H_2O accessories was used to determine ^{222}Rn and ^{220}Rn activity in soil gas and outdoor air, and also ^{222}Rn activity in water respectively. The RADON-JOK equipment was used to measure the soil gas permeability. A portable NaI (Tl) survey meter was used to measure the terrestrial gamma dose rate. The ^{222}Rn concentration in soil gas ranged from 0.11 to 434.5 kBq m^{-3} with a mean of 18.96 ± 6.66 kBq m^{-3}. The soil gas permeability ranged from 5.2×10^{-14} to 5.2×10^{-12} m^2, with a mean of 5.65×10^{-13} m^2. Geogenic radon potential (GRP) values were computed from the ^{222}Rn activity and soil gas permeability data. The range of GRP values was from 0.04 to 154.08. High GRP values were identified at Perak Tengah (36.95), Kampar (43.42), Kuala Kangsar (44.78), Hillir Perak (54.34), and Manjung (154.08) districts. Statistical correlation analysis indicates that the estimated GRP data is strongly correlated with the measured ^{222}Rn in soil gas. The ^{222}Rn activity in water samples was in the range of 0.04 to 3.98 Bq l^{-1}, with a mean of 0.69 ± 0.27 Bq l^{-1}. The annual effective dose for inhalation and ingestion of ^{222}Rn in water ranged from 0.102 to 9.954 µSv y^{-1} and 0.102 to 10.112 µSv y^{-1} respectively. The mean annual effective dose of inhalation and ingestion were 1.73 and 1.76 µSv y^{-1} respectively and were below the world average of 2 µSv y^{-1}. The ^{222}Rn activity in outdoor air ranged from 5.79 to 5110 Bq m^{-3}, with a mean of 320.03 Bq m^{-3} which is higher than the EPA level of 14.8 Bq m^{-3}. The ^{220}Rn activity in the soil gas range from 0.0 to 562.58 kBq m^{-3} with a mean of 37.69 kBq m^{-3}. The highest ^{220}Rn activity was recorded in the granite and Triassic-Jurassic geological formations of the study area. Elevated ^{220}Rn activity was found in peat, riverine, and granite source soils. The ^{220}Rn activity in outdoor air ranged from 0 to 4226.70 Bq m^{-3}, with a mean of 228.12 Bq m^{-3} which is higher than the UNSCEAR value of 10 Bq m^{-3}. The gamma dose rate results ranged from 98.31 to 3769.10 nGy h^{-1} with a mean of 446.27 nGy h^{-1}. The mean total effective dose from ^{222}Rn, ^{220}Rn, and outdoor gamma dose exposure of 1825 h (5 h per day) was 3.75 mSv y^{-1} which is above the world average of 2.4 mSv y^{-1}. Pioneer radon, thoron, and GRP maps were developed to highlight radon-prone points in the area under investigation. The maps assist in human health risk assessment and risk reduction since it indicates the source of radon and thoron.

ABSTRAK

Radon dan isotop anaknya wujud dalam persekitaran semula jadi dan boleh menyumbang dengan ketara terhadap pendedahan manusia kepada sinaran mengion. Mengetahui tahap radon alam sekitar boleh membantu agensi perlindungan radiologikal dalam penggubalan dasar. Penyelidikan ini bertujuan untuk mengukur aktiviti radon (^{222}Rn) dan thoron $^{(220}$Rn), dan pemetaannya, untuk mengenal pasti kawasan berisiko di negeri Perak, Malaysia. Pengesan RAD7 yang digandingkan dengan kuar tanah, persampelan udara, dan aksesori RAD-H_2O digunakan untuk menentukan aktiviti ^{222}Rn dan ^{220}Rn masing-masing dalam gas tanah dan udara luar, serta aktiviti ^{222}Rn di dalam air. Peralatan RADON-JOK digunakan untuk mengukur kebolehtelapan gas tanah. Meter tinjau mudah alih NaI (Tl) digunakan untuk mengukur kadar dos gama daratan. Kepekatan ^{222}Rn dalam gas tanah adalah antara 0.11 hingga 434.5 kBq m^{-3} dengan min 18.96 ± 6.66 kBq m^{-3}. Kebolehtelapan gas tanah adalah antara 5.2×10^{-14} hingga 5.2×10^{-12} m^2, dengan min 5.65×10^{-13} m^2. Nilai potensi radon geogenik (GRP) telah dikira daripada data aktiviti ^{222}Rn dan kebolehtelapan gas tanah. Julat nilai GRP adalah dari 0.04 hingga 154.08. Nilai GRP yang tinggi dikenal pasti di daerah Perak Tengah (36.95), Kampar (43.42), Kuala Kangsar (44.78), Hillir Perak (54.34) dan Manjung (154.08). Analisis korelasi statistik menunjukkan bahawa anggaran data GRP berkorelasi kuat dengan ^{222}Rn yang diukur dalam gas tanah. Aktiviti ^{222}Rn dalam sampel air adalah dalam julat 0.04 hingga 3.98 Bq l^{-1}, dengan min 0.69 ± 0.27 Bq l^{-1}. Dos berkesan tahunan untuk penyedutan dan pengingesan ^{222}Rn dalam air adalah masing-masing di antara 0.102 hingga 9.954 µSv t^{-1} dan 0.102 hingga 10.112 µSv t^{-1}. Min dos berkesan tahunan penyedutan dan pengingesan adalah masing-masing 1.73 dan 1.76 µSv t^{-1} dan di bawah purata dunia 2 µSv t^{-1}. Aktiviti ^{222}Rn di udara luar adalah di antara 5.79 hingga 5110 Bq m^{-3}, dengan min 320.03 Bq m^{-3} yang lebih tinggi daripada paras EPA iaitu 14.8 Bq m^{-3}. Aktiviti ^{220}Rn dalam julat gas tanah adalah dari 0.0 hingga 562.58 kBq m^{-3} dengan min 37.69 kBq m^{-3}. Aktiviti ^{220}Rn tertinggi direkodkan dalam pembentukan geologi Triassic-Jurassic di kawasan kajian ini. Kenaikan aktiviti ^{220}Rn ditemui di punca tanah gambut, tanah sungai dan granit. Aktiviti ^{220}Rn di udara luar adalah antara 0 hingga 4226.7 Bq m^{-3}, dengan min 228.12 Bq m^{-3} yang lebih tinggi daripada nilai UNSCEAR iaitu 10 Bq m^{-3}. Dapatan kadar dos gama adalah antara 98.31 hingga 3769.1 nGy j^{-1} dengan min 446.27 nGy j^{-1}. Min jumlah dos yang berkesan daripada ^{222}Rn, ^{220}Rn dan dedahan dos gama luaran selama 1825 j (5 j per hari) ialah 3.75 mSv y^{-1} iaitu melebihi purata dunia 2.4 mSv t^{-1}. Peta perintis radon, toron dan GRP dibangunkan untuk menonjolkan kawasan siasatan yang terdedah kepada radon. Peta ini membantu dalam penilaian risiko kesihatan manusia dan pengurangan risiko kerana ia menunjukkan punca asal radon dan toron.

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LIST OF ABBREVIATIONS

AED	-	Annual Effective Dose
CRPS	-	Continuous Ranked Probability Score
DCF_r	-	Dose Conversion Factor
EEC	-	Equivalent Equilibrium Concentration
FAO	-	Foods and Agricultural Organization
FWHM	-	Full Width at Half Maximum
GRP	-	Geogenic Radon Potential
HPGe	-	High purity Germanium
IAEA	-	International Atomic Energy Agency
ICRP	-	International Commission on Radiological Protection
MDA	-	Minimum Detective Activity
ME	-	Mean Error of Prediction
MSE	-	Mean Standardized Error
RI	-	Radon Index
RMSE	-	Root-Mean-Square Error
RPA	-	Radon Prone Area
RSG	-	Radon in Soil Gas
SE	-	Standard Error
TAED	-	Total Annual Effective Dose
UNESCO	-	United Nations Education Scientific and Cultural Organization
UNSCEAR	-	United Nations Scientific Committee on the Effects of Atomic Radiation
USEPA	-	United States Environmental Protection Agency
UTM	-	Universiti Teknologi Malaysia
WHO	-	World Health Organization
WL	-	Working Level

LIST OF SYMBOLS

γ	-	Gamma radiation
α	-	Alpha radiation
λ	-	Decay constant
t	-	time
$T_{1/2}$	-	Half-life
A	-	Activity
Gy	-	Gray
nGy	-	nano-Gray
Sv	-	Sievert
μSv	-	micro-Sievert
μR	-	micro-Roentgen
D,d	-	Diameter
L	-	Length
v	-	volume
π	-	Pi
h	-	Hour
s	-	Seconds
k	-	Soil permeability
Q,q	-	Gas flow
μ	-	Dynamic viscosity
F	-	Shape factor
keV	-	Kilo-electron-volt
j	-	Joule
Bq	-	Becquerel
Kg	-	Kilogram
m^2	-	Square meter
m^3	-	Cubic meter
^{222}Rn	-	Radon
^{220}Rn	-	Thoron
C_r	-	Mean radon or thoron activity concentration.

^{238}U	-	Uranium-238
^{232}Th	-	Thorium-232
^{40}K	-	Potassium-40
Ra_{eq}	-	Radium equivalent
H_{ex}	-	External hazard index
H_{in}	-	Internal hazard index
$H_{\gamma\text{-rad}}$	-	External gamma radiation dose
F_r	-	Equilibrium factor

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CHAPTER 1

INTRODUCTION

1.1 Background of the study

Natural radionuclides are the major contributors to human exposure to ionizing radiation (Faanu, 2012). The major natural radionuclides of concern are thorium (^{232}Th) and uranium (^{238}U) as well as potassium (^{40}K). Radon is a naturally occurring radioactive gas which comprises three significant naturally occurring isotopes, radon (^{222}Rn), thoron (^{220}Rn), and actinon (^{219}Rn). These isotopes belong to ^{238}U, ^{232}Th, and ^{235}U decay series, respectively (Mittal et al., 2016). ^{220}Rn has a half-life of about 55.6 seconds, whereas ^{222}Rn has a half-life of 3.82 days (~ 92 hours). In radiation protection against radon gases, ^{222}Rn and ^{220}Rn are the main sources of exposure (ICRP, 2017). ^{222}Rn and ^{220}Rn are from different radioactive decay chains, their ratio or that of their decay products depends on the ratio of ^{238}U and ^{232}Th in rocks and soils of a location (UNSCEAR, 2000b).

Generally, when the ^{238}U and ^{232}Th are high in the environment, ^{222}Rn and ^{220}Rn gases at that site are relatively high too (Syarbaini & Pudjadi, 2015). Elevated ^{222}Rn and ^{220}Rn concentration is associated with granite rocks rich in ^{238}U and ^{232}Th respectively (Mihci, 2010). The soil derived from granite will have higher radioactivity than the soil from the other rock types (Rani & Singh, 2005; Saleh et al., 2013). Significant ^{238}U and ^{232}Th are naturally present in rocks, soils, air, and water, which can be ushered into the environment by diffusion and other means. Thus, resulting in the accumulation and high concentration of ^{222}Rn and ^{220}Rn in the environment (Duggal et al., 2014).

Soil gas permeability is a fundamental parameter for the determination of ^{222}Rn and ^{220}Rn gas mobility (Neznal & Neznal, 2005). The presence of a superficial soil layer with low permeability could imply an increase in the accumulation of ^{222}Rn and

^{220}Rn below, and may also lead to a considerable decrease in the radon's soil-atmosphere flux (Johner & Surbec, 2001). The ^{222}Rn and ^{220}Rn concentration in soil gas is directly dependent on the geological characteristics of the area and can be strongly influenced by soil permeability (Lara et al., 2015).

Studies of ^{222}Rn and its progeny have contributed to many scientific fields (radiotherapy, meteorology, and geophysics) but it is best known for being a significant cause of lung cancer. From the work of Paracelsus and Agricola (1950), it is clear that ^{222}Rn was responsible for the fatal lung disease of silver miners in Saxony and Bohemia (Czech Republic) in the 16th century. In the 20th century, the causal role of ^{222}Rn and its short-lived progeny in lung cancers has been established (Tarsheen et al., 2012). In the 21st century, there has been an ever-growing interest in the health effects of exposure of the general public to ^{222}Rn (McLaughlin, 2013). The energy transferred by radon alpha and beta emitters to a body can be quantized as the absorbed dose, and the probability of affecting the human biological system is directly related to the absorbed dose (ICRP, 1991). The world average annual effective dose to the public is about 2.4 *mSv* per year. The limit for external radiation dose rate is 0.5 μSv h^{-1} for Malaysia (UNSCEAR, 2000b). However, ICRP publication 103 recommends an effective dose of 1 mSv per year for members of the public and 20 mSv per year for the occupationally exposed (ICRP, 2007).

Radon and its isotopes, parent radionuclides, and decay products all contribute to an average effective dose of 1.26 mSv y^{-1} (UNSCEAR, 2000a). The respective dose contributed by the radon isotopes and their progeny are largely dependent on the local geology or ratio of the concentration of ^{238}U and ^{232}Th in the soil (Ramli et al., 2005). The short-lived decay products (^{214}Po and ^{218}Po alpha emitters with energy 5.5 MeV) of ^{222}Rn when inhaled can deposit along the trachea and within the lungs and can cause significant damage to the internal cells of the bronchioles which may lead to the occurrence of lung cancer. Because of the short half-life (55.6 s) of ^{220}Rn, studies on its exposure have been often ignored by researchers. The other factors responsible for giving it less attention include difficult measurement techniques, low diffusion length, thus leading to negligible contribution of radiation dose to people (Jónás et al., 2016).

Because most of the ^{220}Rn never makes it very far from the granite's surface, the United States environmental protection agency (USEPA) does not consider ^{220}Rn a major contributor to health problems (Alenezy, 2014; Rahman et al., 2008). Nevertheless, several studies in various countries (Japan, China, Czech Republic, Italy, India, Canada, Brazil, Germany, and the USA) have observed high ^{220}Rn in the environment (Ramachandran, 2010; UNSCEAR, 2000a). Other studies have shown that ^{220}Rn and its progeny could account for doses equal to or higher than the ones from ^{222}Rn and its progeny (Cinelli et al., 2015). Considerable data is generated globally on the levels of ^{222}Rn activity concentration and the associated health risks (UNSCEAR, 2006). In contrast, data on ^{220}Rn is scarce due to the general perception that its level is negligible due to its shorter half-life (Jónás et al., 2016).

The ^{222}Rn concentration in water is associated with the bedrock, soil type, presence of faults, porosity-permeability, physiochemical, and nature of the geological aquifers (Ali et al., 2015; Jobbagy et al., 2017). Surface water does not usually contain a significant level of ^{222}Rn because they are exposed and dissolved ^{222}Rn easily escapes to the air as a result of temperature variations in the atmosphere. Nonetheless, appreciable levels are noticed in groundwater specifically when it passes over granite rocks (Ali et al., 2010b; Suresh et al., 2019). The health hazard due to the ingestion of ^{222}Rn from water is lower than that of ^{222}Rn inhalation from the one exhaled from the same water source (Duggal et al., 2020; Durridge Company RAD7 User Manual, 2015). Thus, it is crucial to appraise ^{222}Rn in water and assess the related ingestion and inhalation doses for the safety of the populace near the water sources.

The ^{222}Rn and ^{220}Rn concentrations in the outdoor air are measured in the number of radioactive decays per second per cubic meter of air (Bq m^{-3}) (Russell & Bradley, 2015). The latter isotope, ^{220}Rn is a daughter of ^{228}Ra from the thorium (^{232}Th) decay series. ^{232}Th also occurs naturally in the earth's crust, thus is responsible for ushering ^{220}Rn to the outdoor air in varying concentrations. The determination of the outdoor concentration of ^{222}Rn, ^{220}Rn, and their decay products in the lower layers of the atmosphere is not easy, because of the influence of atmospheric factors (place, time, height above the ground, and meteorological conditions). The determination of the outdoor concentration levels of ^{222}Rn and ^{220}Rn also provides a baseline for indoor levels respectively (UNSCEAR, 2006). Large volumes of air with a high concentration of ^{222}Rn and ^{220}Rn releases into the outdoor atmosphere could cause high health risks to the public (Ramola et al., 2008; UNSCEAR, 2000b).

The assessment of ^{222}Rn and ^{220}Rn in any environment (soil, water, and outdoor air) is basic for the protection of the population from exposure. It is important for such action plans to accommodate the identification of the radon-prone areas (RPA) [i.e areas with the potential to generate higher indoor radon levels](ICRP, 2007). This is what this study aims to achieve for Perak state.

1.2 Problem statement

The exposure of human beings to ionizing radiation from natural sources is a continuing and inescapable feature of life on earth. More than half of the biological effects of ionizing radiation come from the radioactivity of ^{222}Rn gas and its daughter isotopes (Csanádet al., 2012). There are no immediate symptoms that alert one of the presences of radon. It typically takes years of exposure before any problem surfaces. Assessment is the only way to know an environment's radon levels. The factors that affect the ^{222}Rn and ^{220}Rn concentration of an area are dynamic, although the instruments and methods of measurement may be the same. This, therefore, makes each site unique because of its peculiar geological and environmental setting (WHO, 2009). The study of ^{222}Rn and ^{220}Rn levels has become a sizzling issue in recent years (Wang et al., 2012). However, increased awareness is not directly translating into action in many countries.

The previous study of activity concentration of ^{238}U and ^{232}Th based on soil types in Perak state has indicated activities higher than the UNSCEAR (2000a) reference values (Nursama et al., 2013; Ramli et al., 2016; Zalina et al., 2010). This should be given more attention since the respective dose contributed by the ^{222}Rn and ^{220}Rn isotopes and its progeny are largely dependent on the local geology or ratio of the concentration of ^{238}U and ^{232}Th in the soil (Ramli et al., 2005). Limited data are available in the literature for ^{222}Rn and ^{220}Rn concentrations in Perak state Malaysia.

In Perak state and Malaysia in general, to date, there have been no significant studies on a national level that would include mapping of ^{222}Rn or ^{220}Rn, despite its apparent health risk (Ahmad et al., 2017). This research seeks to properly quantify the concentrations of ^{222}Rn and ^{220}Rn, and also their mapping, to identify risk areas. This will provide a database of information that could be useful for highlighting regions of elevated ^{222}Rn and ^{220}Rn levels in Perak state Malaysia. This research will attempt to investigate the following:

a. What is the soil permeability level of the study location?
b. What are the ^{222}Rn and ^{220}Rn concentration levels of the study area?
c. Do these ^{222}Rn and ^{220}Rn levels constitute any health hazards?
d. What is the association between natural radionuclides with ^{222}Rn and ^{220}Rn concentrations?
e. Is there any correlation between soil gas ^{222}Rn and ^{220}Rn with soil type/geology?
f. What is the possibility of developing geogenic radon potential (GRP), ^{222}Rn, and ^{220}Rn concentration maps for the study area?

1.3 Objectives of the study

This research aims to determine radon-prone areas in the study location through the assessment of ^{222}Rn and ^{220}Rn activity in soil gas and soil permeability. The objectives of the research are:

(a) To assess the soil permeability.

(b) To determine the level of ^{222}Rn and ^{220}Rn concentrations in soil gas, water, and outdoor air.

(c) To estimate the health effects of ^{222}Rn and ^{220}Rn concentrations.

(d) To measure the gamma dose rate, and activity concentrations of ^{226}Ra (^{238}U), ^{228}Ra (^{232}Th), and ^{40}K in soil and examine the relation with ^{222}Rn and ^{220}Rn, respectively.

(e) To classify the activity concentrations of ^{222}Rn and ^{220}Rn based on geological and soil formation and establish a model to derive the activities.

(f) To develop GRP, ^{222}Rn, and ^{220}Rn concentration maps of Perak state.

1.4 Scope of the study

The study was carried out in Perak state Malaysia. The tin mining areas of the state were of special interest in the study. The sampling was carried out over four geological units and six major soil types covering thirteen districts of the state. The sampling sites covering each geological formation, soil type, and district in Perak state were pre-selected employing ArcGIS Pro software, using geographical coordinates.

This study is focused on the in-situ measurements of ^{222}Rn and ^{220}Rn concentration in soil gas, and outdoor air, as well as the soil gas permeability. ^{222}Rn activity in water samples from lakes, hot springs, and rivers was also assessed and the effective inhalation dose by virtue of ^{222}Rn in water was estimated. The relative humidity and temperature were as well recorded during the measurements of ^{222}Rn and ^{220}Rn in soil gas and outdoor air. The terrestrial gamma radiation dose (TGRD) of each sampling site was also measured one meter above the ground. Soil samples were collected from each measurement site and taken to the laboratory for measuring the activity concentration of ^{226}Ra (^{238}U), ^{228}Ra (^{232}Th), and ^{40}K in the soil samples. The radium equivalent, external hazard index, and internal hazard index were estimated.

The GRP of the study location was estimated. The GRP and its correlation to the other measured parameters were tested using Pearson's correlation to determine their statistical relationship.

Spatial interpolation of ^{222}Rn in soil gas, ^{220}Rn in soil gas, soil permeability, and GRP were performed to obtain a map for each parameter's spatial distribution. The error of prediction map for the GRP was developed to assess the accuracy of the spatial analysis model.

1.5 Significance of the study

Recently, there has been increased interest shown by researchers' world over on the importance of monitoring ^{222}Rn and ^{220}Rn, and its health impact, since it is a major contributor to the ionizing radiation dose received by the general public (WHO, 2009). This study is aimed at mapping ^{222}Rn and ^{220}Rn prone areas in Perak state, which will help in identifying areas with activities above the international reference levels.

This study has the potential to significantly provide information and create awareness that can influence public health policy concerning ^{222}Rn and ^{220}Rn testing protocols in Perak state and Malaysia in general. The mapping will improve the definition of priority areas for ^{222}Rn and ^{220}Rn risk management and contribute baseline data on activity concentration for a better knowledge of exposure in Perak state Malaysia. Also, a ^{222}Rn and ^{220}Rn potential map is a valuable tool in land-use planning, as it will help the authorities to take decisions in targeting priority areas to prevent new buildings on high radon potential areas (WHO, 2009). Thus, the findings of this research will be quite valuable to the environmental and radiological protection agencies as well as the Perak state populace, since geological-based radon analysis measures the dissemination of radon in diverse locations.

1.6 Thesis outline

The thesis is outlined in five chapters. Chapter one consists of an introduction of the research, followed by a background of the study, problem statement, objectives of the study, scope, and the thesis outline. Chapter two contains the theoretical background of the study and literature review. It consists of radioactivity terminologies, soil permeability. radon and thoron in the environment, a review of radon and thoron activity concentration studies for different countries and Malaysia, and the health effects of radon and thoron, as well as the terrestrial gamma radiation dose rate. Chapter three outlines the methodology and Instruments used to obtain data in the study. Chapter 4 presents the results and analysis of the obtained data in the study. Chapter 5 consists of the conclusions of the study and recommendations for further research.

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LIST OF PUBLICATIONS

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1. **Nuhu, H.,** Hashim, S., Saleh, M.A., and Sanusi, M.S.M. (2020). Radon activity concentration measurements in water sources from Perak state Malaysia. *Journal of radiation research and applied science*. 13(1), 665 - 671. https://doi.org/10.1080/16878507.2020.1820270. **(Q3, IF:1.770)**.

2. **Nuhu, H.,** Hashim, S., Saleh, M.A., Sanusi, M.S.M., Alomari, A.H., Jamal, M.H., Abdullah, R.A., and Hassan, S.A. (2021). Soil gas radon and soil permeability assessment: Mapping radon risk areas in Perak State, Malaysia. *PLOS ONE*.16(7), 1 – 17. https://doi.org/10.1371/journal.pone **(Q2, IF:3.240)**

3. **Nuhu, H.,** Hashim, S., Sanusi, M.S.M., and Saleh, M.A. (2021) Radiological assessment subjected to outdoor radon and thoron concentrations and terrestrial gamma radiation measurements in Perak Malaysia. *Applied radiation and Isotopes*. 179(2022), 1-5. https://doi.org/10.1016/j.apradiso.2021.109991 **(Q2, IF:1.513)**.

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1. **H. Nuhu**, S. Bin Hashim, M. Aziz Saleh, M. Syazwan Sanusi, W.M.S.B. Wan Hassan (2020). Outdoor radon, thoron, and terrestrial gamma radiation measurements and estimation of radiation dose in Perak Malaysia. *XX International Symposium on solid-state dosimetry.* **ISSSD Proceedings Vol.1, 2020 Sociedad Mexicana de Irradiación y Dosimetría.** 97 - 109