ISSN Online: 2756-3898, ISSN Print: 2714-500X https://doi.org/10.47514/phyaccess.2026.6.1.013

Assessment of Natural Radioactivity and Associated Radiological Risks in Cements Produced and Used as Building Materials in Malawi

Aeron M A Nahuku[1], Alinue Musopole[1], Samson Nyirenda[2], Fabiano G D Thulu[3], Estiner W Katengeza[3], Bernard Thole[3], and Chikumbusko C Kaonga[3]

[1] Department of Foundation Sciences, Kamuzu University of Health Sciences, Blantyre, Malawi
[2] Department of Testing and Services, Malawi Bureau of Standards, Blantyre, Malawi
[3] Department of Physics and Biochemical Sciences, Malawi University of Business and Applied Sciences, Blantyre, Malawi

Corresponding E-mail: anahuku@kuhes.ac.mw

Received 18-02-2026
Accepted for publication 13-04-2026
Published 22-05-2026

Abstract

This study assessed the natural radioactivity and associated radiological health risks of commercially available cement brands produced and distributed in Malawi to evaluate compliance with international radiation safety standards for building materials. Cement samples were analyzed for ^{226}Ra, ^{232}Th, and ^{40}K activity concentrations using high-purity germanium (HPGe) gamma-ray spectrometry. The mean activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were 29.9 ± 4.6, 17.3 ± 2.8, and 309.7 ± 34.8 Bq kg^{-1}, respectively, all below the UNSCEAR recommended limits. The mean radium equivalent activity (Ra$_{eq}$) was 78.4 ± 8.5 Bq kg^{-1}, significantly lower than the recommended limit of 370 Bq kg^{-1}. Calculated radiological hazard indices, including external hazard index, internal hazard index, gamma index, and alpha index, were all below the recommended safety threshold of unity. The mean outdoor and indoor absorbed dose rates were 36.2 ± 8.5 and 72.5 ± 7.5 nGy h^{-1}, respectively, while the corresponding annual effective doses were 0.044 ± 0.0046 and 0.178 ± 0.019 mSv y^{-1}. The evaluated excess life cancer risk values were well below internationally accepted reference limits. These results demonstrate that the investigated cement products do not pose significant radiological hazards to the public and are safe for use as construction material. However, periodic assessment and monitoring of these natural radionuclides in cements and other building materials in Malawi are highly recommended.

Keywords: NORM, Cement, Specific activity, Gamma spectrometry, Radiological hazard indices.

I. INTRODUCTION

Cement is a basic construction material and contains Naturally Occurring Radioactive Materials (NORM) such as uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K) and their progenies [1 - 3]. Several factors, such as soil type and elevation, can influence regional radioactivity levels due to exposure to rocks that are rich in uranium [4]. Climatic and environmental conditions like high rainfall can also facilitate the removal of radon and reduce its accumulation in buildings [2 - 5]. Exposure to natural radiation is therefore intrinsic for people who work and live in cement-built buildings [6 - 7].

Building materials, such as cement, have contributed significantly to the proliferation of internal and external dose rates, making it a concern for the public and the environment, particularly when normal levels of natural radionuclides are exceeded [8-11]. As such, international organizations like the International Commission on Radiological Protection (ICRP) and the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) have set reference levels as a way to safeguard the environment, workers, and the public from the effects of ionizing radiation, even from building materials [12 - 13]. Recent studies and international guidelines indicate that the recommended reference activity concentration levels for naturally occurring radionuclides in building materials are 400 Bq kg^{-1} for ^{40}K, 35 Bq kg^{-1} for ^{226}Ra, and 30 Bq kg^{-1} for ^{232}Th [14 - 16]. The European directive Euratom 2013/59 also recommends that building materials' Activity Concentration Index (ACI) must always be less than 1 for it to be suitable for use in construction [10].

Following such recommendations, several radiological risk assessments in cements have been conducted worldwide and have shown adherence to international safety guidelines. For example, a study in Tanzania found that radiological indices for cement were sixty percent lower than the recommended limit of "1" in building materials, although raw materials from Mbeya and Songwe bordering Malawi in the North were excluded [17]. Also, radioactivity data for some cements from Spain and other parts of Europe have shown lower activities in white cements than in conventional cements, but high in Calcium Aluminate Cements (CAC) within the ^{232}Th series [10]. No significant radiological risks have also been reported from studies in Ethiopia [4], Nigeria [8], Jordan [3], and India [18]. Existing literature in Malawi indicates that research has primarily focused on cement properties like appropriateness of local materials such as clay and limestone to manufacture Limestone Calcined Clay Cement (LC3) systems [19]. Other researchers have focused on industrial contributions to pollutants in urban dust, and heavy metals analysis in soils near industrial areas like cement plants [20 - 21].

Despite these findings, no studies on the radioactivity of cement produced and used as a building material in Malawi have been reported. This study, therefore, assessed NORM and associated risks in Malawian cements to determine the industry's compliance with international safety limits. Understanding these crucial radiological characteristics would help improve safety practices for workers and the public in the assessment of protection, but also the development of safety recommendations for the implementation and control of these radioactive elements in building materials [2]. The data could further inform policy and regulatory standards and guidelines for the cement industry, but also other related industries. Furthermore, demonstrating compliance could eventually enhance the competitiveness of Malawian cement within regional and global markets and also improve its supply chain strategies. Commodities that meet international standards help to improve supply chain strategies and efficiencies for new markets and later support industry sustainability and national economic growth [22 - 23].

II. MATERIALS AND METHODS

A. Design and Sampling

This study was descriptive and quantitative in nature, and adopted a purposive sampling technique to collect the cement samples. The technique was not only economic, but it also ensured that selected cement samples reflected the variety of cements produced and widely used as a building material in Malawi by collecting multiple cement samples of a particular type from different distributors or suppliers and mixing them thoroughly to form a single sample. The approach ensured that the cements were a representative of the local cement type sold on the majority of the national market, which is dominated by local cements alongside other imported cement brands. It also helped to avoid bias from a single source.

Ten (10) types of locally produced cement commonly used in Malawi were collected in triplicate, with each sample weighing 1 kg. Composite samples were prepared by thoroughly mixing cement from multiple distributors and suppliers to ensure a representative sample of each cement type available on the national market. The samples were obtained from major dealers and distributors in Blantyre, Mangochi, Lilongwe, and Kasungu districts, capturing cement brands widely accessible to the public across the country and improving the external validity of the study. All samples were collected in powdered form as supplied by the manufacturers. The cement samples were then packaged in sealed containers and assigned identification codes BB7250–BB7257, BB11529, and BC5037 before being transported to the laboratory for analysis. Only cement products manufactured in Malawi were included in this study.

B. Sample Preparation

All cement samples were dried in an oven for 24 hours and then placed in Marinelli containers, which were sealed with parafilm. A storage aging period of 20 days before gamma spectrometric measurements was considered to allow for samples to reach secular equilibrium between ^{226}Ra and its short-lived daughter nuclides. At this point, the rate of decay of the parent radionuclide is balanced by the rate of the daughter radionuclide, resulting in a stable concentration of both radionuclides [24].

C. Radioactivity Measurement

Radioactivity measurements were carried out using a calibrated High Purity Germanium (HPGe) gamma ray spectrometer (GCD 30200, Baltic Scientific Instruments, Riga, Latvia) shielded with lead coupled to a multichannel analyzer (BGS Elektronik GmbH, Germany). The detector's characteristics included: an energy range of 40 keV – 10 MeV, relative efficiency of 31%, a Full Width Half Maxima (FWHM) energy resolution of 1.868 keV at the 1.332.5 keV for cobalt-60 (^{60}Co), peak to Compton ratio of 58.1 keV, and a FWHM for ^{57}Co of 1.004 keV at 122 keV.

Energy and efficiency calibrations were performed using certified mixed gamma-ray standard sources, provided by Echert and Ziegler. The energy calibration range was from 46.5 to 1836 keV. Specific gamma emission photopeaks of lead-214 (^{214}Pb-214) at 351.9 keV (35.6%) and bismuth-214 (^{214}Bi) at 609.3 keV (45.49%) and 1120 keV (14.92), were used to determine activities of ^{226}Ra. ^{232}Th was determined via actinium-228 (^{228}Ac-228) at 911.12 keV (25.8%) and titanium-208 (^{208}Tl) at 583.2 keV (85.0%). Finally, ^{40}K activities were obtained from its 1461 keV.

The spectra were read with SpectraLineGP software. The background measurements were also carried out to serve as a reference due to the system's components and the surrounding environment. This was crucial for testing the accuracy of the detection system [5], [15]. Every cement sample was measured for 48 hours for radioactivity. This is a standard procedure as specified by the Malawi Bureau of Standards (ISO 20042:2019 (EN)). Measurements over such a long time enable considerable counts for natural radionuclide detection [4]. It is important to note that ^{226}Ra was used in this study instead of ^{238}U because the decay chain segments beginning with ^{226}Ra are mostly considered more significant than those of the ^{238}U sequence [25].

D. Estimation of Radiological Parameters

Radiological parameters such as radium equivalent, external and internal hazard indices, gamma index, alpha index, equivalent doses, and excess life cancer risk were calculated in order to determine the cements' associated radiological risk. All the estimated values were compared with those from other studies in the literature and UNSCEAR.

1) Radium Equivalent (Ra_{eq})

Calculations of Ra_{eq} were done in order to describe the gamma output from different composites of uranium, thorium, and potassium in the samples. This is because the distribution of NORM in building and other materials is often considered uneven [16], [26]. Cumulatively, the Ra_{eq} activity from the measured natural radionuclides was calculated in Becquerels per kilogram (Bq kg^{-1}) using (1) [16].

$$\mathrm{Ra_{eq}} = \left(\frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810}\right) \times 370 \qquad (1)$$

Here, A_{Ra}, A_{Th}, and A_K are the measured activities for ^{226}Ra, ^{232}Th, and ^{40}K, respectively, and they apply to all subsequent equations. Literature indicates that the maximum permissible limit of Ra_{eq} for NORM in building materials should not exceed 370 NGy h^{-1} [16].

2) External hazard index (H_{ex}) and Internal Hazard Index (H_{in})

External and internal exposure to gamma radiation from natural radionuclides was conducted through the calculation of external and internal hazard indices (H_{ex} and H_{in}). Equations (2) and (3) were used to calculate H_{ex} and H_{in}, respectively. The internal hazard index primarily assesses the radiation hazard posed by radon and its short-lived daughter products, which are hazardous to the respiratory organs. Both H_{ex} and H_{in} values should not exceed the value of "1" as set by the UNSCEAR [26].

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \qquad (2)$$

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \qquad (3)$$

3) Gamma Index (I_γ)

The gamma index primarily quantifies the level of radioactivity in a specific environment or material. It determines the risk levels of gamma radiation that's associated with the natural radionuclides [16]. As such, the index acts as a screening tool for identifying materials that might be of radiological concern when used. The I_γ values were calculated as in (4). The recommended maximum safety limit for gamma indices must not exceed the value of "1" [14].

$$I_\gamma = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000} \qquad (4)$$

Here, 300, 200, and 3000 NGy h^{-1} are the reference values set for ^{226}Ra, ^{232}Th, and ^{40}K radionuclides, respectively [2].

4) Representative Level Index (RLI)

RLI also plays a crucial role when evaluating gamma radiation hazard characteristics related to NORM in various materials, such as building materials or soil [27]. *RLI* values were calculated using (5), and their values must also be less than the recommended value of "1" [27].

$$\mathrm{RLI} = \frac{A_{Ra}}{150} + \frac{A_{Th}}{100} + \frac{A_K}{1500} \qquad (5)$$

5) Excess Alpha Radiation Index

Excess alpha radiation due to radon inhalation resulting from the construction materials is calculated in relation to activities of ^{226}Ra, ^{232}Th, and ^{40}K. Equation (6) was used for the calculations of alpha indices, where Ra_{eq} was the calculated radium equivalent. If the samples are to be deemed within the safety limits, the calculated values must also be less than the recommended value of "1" [16].

$$I_\alpha = \frac{\mathrm{Ra_{eq}}}{200} \qquad (6)$$

Here, 200 NGy h^{-1} is considered as the guiding reference value set for uranium [2].

6) Absorbed Dose Rates (ADR)

The ADR for both outdoor and indoor air environments was determined from the gamma radiation emitted by the radionuclides ^{226}Ra, ^{232}Th, and ^{40}K present in cement. The calculations were performed using (7) and (8), assuming exposure at a height of 1 m above the ground surface with a uniform distribution of naturally occurring radioactive materials (NORM). The outdoor and indoor ADR values were expressed in Grays per hour ($Gy\ hr^{-1}$).

$$D_{out}(\mathrm{nGy\ hr^{-1}}) = 0.427A_{Ra} + 0.604A_{Th} + 0.042A_K \qquad (7)$$

$$D_{in}(\mathrm{nGy\ hr^{-1}}) = 0.92A_{Ra} + 1.1A_{Th} + 0.084A_K \qquad (8)$$

7) *Annual Effective Dose Equivalent (AEDE)*

Radiation exposure that a person receives over one year was determined by calculating the AEDE in milli Sieverts per year (mSv y^{-1}). Yearly effective doses are, among others, helpful in long-term health risk assessments due to exposure to radiation and a demonstration of compliance with dose limits for regulatory purposes [28]. Indoor and outdoor AEDE were estimated using (9) and (10), respectively.

$$\text{AEDin} = \text{ADR} \times 8760 \times 0.8 \times 0.7 \times 10^{-6} \quad (9)$$

$$\text{AEDout} = \text{ADR} \times 8760 \times 0.2 \times 0.7 \times 10^{-6} \quad (10)$$

Here, ADR is the absorbed dose rate in $\mu Sv\ hr^{-1}$, total time is in hours in one year (8760 hrs.), while 0.8 and 0.2 are the indoor and outdoor occupancy factors based on the fact that annually, humans spend almost 80% of their time indoors and 20% outdoors, respectively. The value of $0.7\ Sv\ Gy^{-1}$ is the dose conversion factor [29] - [31].

8) *Excess Lifetime Cancer Risk (ELCR)*

Long-term exposure to natural radioactivity, especially in settlement areas, may have negative consequences such as cancer [25]. ELCR measures the probability of one developing cancer over a lifetime due to natural radionuclides in building materials. This was estimated using (11) and (12), where AEDE is the annual effective dose equivalent, and LS is the average world life expectancy. In this case, 70 years was considered, and RF is a risk factor of 0.05 when stochastic impacts are considered [8], [31].

$$\text{ELCR}_{\text{in}} = \text{AEDE}_{\text{in}} \times \text{LS} \times \text{RF} \quad (11)$$

$$\text{ELCR}_{\text{Out}} = \text{AEDE}_{\text{Out}} \times \text{LS} \times \text{RF} \quad (12)$$

9) *Annual Gonadal Dose Equivalent (EGDE)*

AGDE assesses the potential genetic risk associated with radiation exposure based on the yearly dose equivalent received by the population's reproductive organs (gonads), bone marrow, and bone surface cells. Bone marrow effects may cause a reduction in red blood cells, which might be replaced with white blood cells. This could result in the development of blood cancer [32]. AGDE was calculated using (13), and according to the international safety limits, 0.3 mSv y^{-1} is the recommended set value for AGDE [32].

$$\text{AGDE}\ (\text{mSv}\ y^{-1}.) = \frac{(3.09\ A_{\text{Ra}} + 4.18\ A_{\text{Th}} + 0.314\ A_{\text{K}})}{1000} \quad (13)$$

10) *Statistical Analysis*

Summary statistics were done using Microsoft Excel (MS-Excel), IBM SPSS Statistics version 23, and R-Studio. Data were summarized using descriptive tools including tables, bar graphs, medians, and inter-quartile ranges. Sample medians were compared with the recommended international safety limits indicated in the 2008 report of the UNSCEAR using sign test. The test is non-parametric and enables researchers to analyse how divergent median values are from zero or reference values [33]. It is effective when comparing the sample median against a specific, predefined standard limit or target value. Even with limited rigor, the test is considered an excellent exploratory test [33]. The approach was therefore ideal for the study due to small sample sizes, and assumed that the data was not normally distributed.

For each comparison, the null hypothesis (H_0) stated that the median values of the measured radiological parameters did not exceed the corresponding international reference limits, indicating no evidence of elevated radiological levels relative to the recommended standards. The alternative hypothesis (H_1) stated that the median values were greater than the prescribed reference limits, suggesting elevated radionuclide concentrations or radiological risk parameters beyond internationally accepted safety thresholds. A significance level of 0.05 was adopted for all statistical analyses. Thus, p-values less than 0.05 were considered statistically significant and sufficient to reject the null hypothesis in favor of the alternative hypothesis. Conversely, p-values greater than 0.05 indicated insufficient statistical evidence to conclude that the median values exceeded the recommended safety limits. In addition, the median activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K among the different cement samples were compared using the Kruskal–Wallis test.

III. RESULTS AND DISCUSSION

A. *Specific Activities*

Specific activity measurements for ^{226}Ra, ^{232}Th, and ^{40}K were recorded in NGy h^{-1}, and the results for each cement sample are summarized in Table I.

Table I: Specific activity measurements for ^{226}Ra, ^{232}Th, and ^{40}K in ten (10) cements in Malawi.

Sample ID	Specific Activity (NGy h^{-1}) ^{226}Ra	^{232}Th	^{40}K
BB7250	22.8	17	400
BB7251	11.5	16	510
BB7252	25.5	18.6	410
BB7253	26.1	11	238
BB7254	28.8	11.2	235
BB7255	53	24.7	300
BB7256	58	25.9	309
BB7257	30.4	30.6	340
BB11529	17	-	123
BC5037	25.8	17.9	223
Average	29.9±4.6	17.3±2.76	309.7±34.8

Table I presents the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the analyzed cement samples, showing moderate variations and distinct distribution patterns across the different cement brands. The activity concentrations of ^{226}Ra ranged from 11.5 to 58.2 Bq kg^{-1}, with a mean value of 29.9 ± 4.6 Bq kg^{-1}. The highest values were recorded in samples BB7255 and BB7256, whereas the lowest activity concentration was observed in BB7251. These variations may be attributed to differences in raw material composition and geological characteristics of the source materials used during cement production.

The lowest variability was observed for ^{232}Th, with activity concentrations ranging from 11.0 to 30.6 Bq kg^{-1} and a mean value of 17.3 ± 2.8 Bq kg^{-1}, indicating relatively stable distribution across most samples. Sample BB7257 exhibited comparatively higher ^{232}Th activity concentrations than BB7251 and BB11529. In contrast, ^{40}K exhibited the highest activity concentrations, ranging from 123 to 510 Bq kg^{-1} with an average value of 309.7 ± 34.8 Bq kg^{-1}. Lower ^{40}K activity was observed in BB11529, while elevated values were recorded in BB7250, BB7251, and BB7252.

The predominance of ^{40}K over ^{226}Ra and ^{232}Th is consistent with the mineralogical composition of cement raw materials, particularly potassium-bearing clay and shale constituents commonly used during cement manufacture. Potassium-rich minerals such as feldspars and micas naturally contribute higher ^{40}K activity concentrations relative to uranium- and thorium-bearing minerals. Similar trends, where ^{40}K constitutes the dominant contributor to natural radioactivity in building materials, have been widely reported in previous studies [34].

Recent studies indicate that specific activities for ^{226}Ra, ^{232}Th, and ^{40}K in building cement should not exceed 35 NGy h^{-1}, 30 NGy h^{-1}, and 400 NGy h^{-1}, respectively, as recommended by UNSCEAR [4], [9], [14], [16]. Comparison of the measured specific activities with those recommended by the UNSCEAR is illustrated in Fig. 1, 2, and 3 for ^{226}Ra, ^{232}Th, and ^{40}K, respectively.

When compared with the 2008 UNSCEAR safety limits, all activities were found to be lower than the recommended safety limits except for samples identified as BB7255 and BB7256 for ^{226}Ra, BB7257 for ^{232}Th, and also BB7251 and BB7252 for ^{40}K. However, the overall mean activities for all the samples were all found below the set UNSCEAR recommended limits, which suggests negligible radiological risk under the assumptions applied when cements are used as a building material. The findings are in agreement with other major research findings worldwide, including those from Africa, as illustrated in Table II.

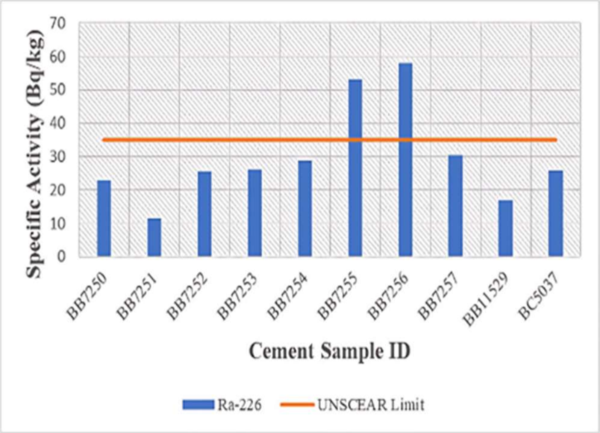

Fig. 1. Comparison of the measured specific activities of ^{226}Ra with UNSCEAR recommended Limits.

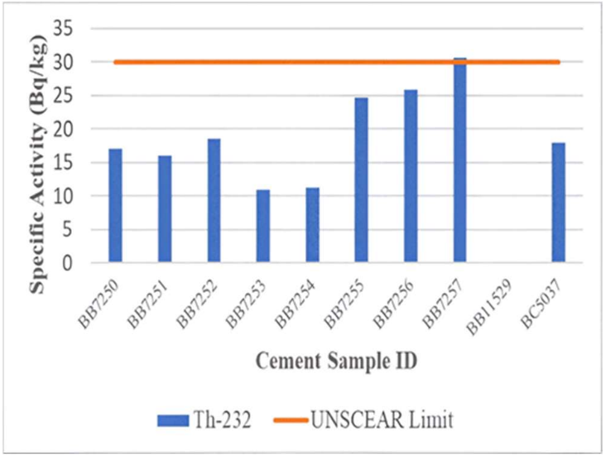

Fig. 2. Comparison of measured specific activities of ^{232}Th with UNSCEAR recommended Limits.

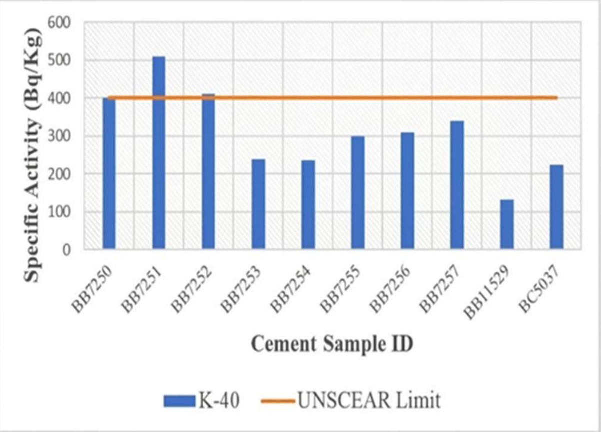

Fig. 3. Comparison of measured specific activities of ^{40}K with UNSCEAR recommended Limits.

Table II: Comparison of radioactivity levels (NGy h⁻¹) in this study with other selected studies worldwide.

Country	^{226}Ra	^{232}Th	^{40}K	Reference
Pakistan	34.2 ± 11.9	29.1 ± 3.6	28 ± 6.9	[35]
Slovak Republic	8.58 - 19.1	9.78 - 26.3	156.5-489.4	[5]
Algeria	1 - 4.2	4.85 -7.7	115.3	[36]
Iran	39.6 ±1.4	28.9±0.9	290.8 ± 12	
Pakistan	26.1	28.6	272.9	
Brazil	41	27	422	[37]
Greece	20	13	241	
India	37	24.1	432.1	
Tanzania	46	28	228	[17]
India	20.3-60.1	18.8 - 60.1	160.9-248.1	[18]
Albania	12.0-16.1	46.2 – 51.2	133.7-168.8	[38]
Nigeria	19.7	7.82	114.3	[8]
Albania	179.7±48.9	55.0 ± 5.8	17.0 ± 3.3	
Algeria	41 ± 7	27 ± 3	422 ± 3	
Cameroon	27 ± 4	15 ± 1	277 ± 117	
China	118.7±14.2	36.1 ± 17.8	444.5±163.1	
Egypt	36 ± 4	43 ± 2	82 ± 4	
Ghana	35.94±0.78	25.44 ±0.8	233 ± 3.95	[39]
Iraq	24.25±1.45	25.41 ± .65	93.17±7.30	
Ethiopia	76.53	81.67	407	[4]
Jordan	79.52±4.67	30.99± 2.85	354.7 ± 9.64	[3]
Malawi	29.89±4.6	17.29±2.76	309.7±34.8	Present study

B. *Radiological Indices*

The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K presented in Table II indicate that most reported values, including those from the present study, were below the UNSCEAR recommended limits and generally consistent with global average levels for building materials. The measured ^{226}Ra and ^{232}Th activities were lower than those reported in Ethiopia [4], Jordan [3], and China [38], but comparable to values reported in Nigeria, Greece, and Pakistan [8], [37]. Although ^{40}K activity concentrations were relatively higher, they remained lower than peak values reported in China [38], Slovakia [5], and India [36]. These variations are likely associated with differences in the geological and geochemical composition of cement raw materials [2], [3], [5].

The calculated radiological parameters, including Ra_{eq}, H_{ex}, H_{in}, I_{γ}, I_{α}, and RLI, also varied among the cement samples. A summary of the estimated radiological indices is presented in Table III.

Table III: Calculated Raeq and other radiological indices

Sample ID	Ra_{Eq} (NGy h⁻¹)	Radiological Indices				
		H_{ex}	H_{in}	I_{γ}	RLI	I_{α}
BB7250	77.9	0.210	0.272	0.294	0.589	0.114
BB7251	73.6	0.199	0.230	0.288	0.577	0.058
BB7252	83.6	0.226	0.295	0.315	0.629	0.128
BB7253	60.1	0.162	0.233	0.221	0.443	0.131
BB7254	62.9	0.170	0.248	0.230	0.461	0.144
BB7255	111.4	0.301	0.444	0.400	0.800	0.265
BB7256	118.8	0.321	0.478	0.426	0.852	0.290
BB7257	100.3	0.271	0.353	0.368	0.735	0.152
BB11529	27.2	0.073	0.119	0.101	0.201	0.085
BC5037	68.5	0.185	0.255	0.250	0.500	0.129
Mean	78.4±8.52	0.212±0.023	0.293±0.034	0.289±0.03	0.579±0.06	0.149±0.02
UNSCEAR Limit	370	<1	<1	≤1	<1	<1

Radium equivalent values ranged from 27.2 NGy h⁻¹ (BB11529) to 118.8 NGy h⁻¹ (BB7256) across the samples. The calculated mean for Raeq was 78.4 ±8.52 NGy h⁻¹. Maximum recommended Raeq in building materials is set at

370 NGy h⁻¹, according to the UNSCEAR set limits [14], [16], [40]. When compared to the set limit, all values are noted to be below the set limit of 370 NGy h⁻¹. These findings imply that all the locally produced cements analyzed in this study pose negligible radiological risks to human health and the environment.

When ^{226}R, ^{232}Th, ^{40}K, and Ra_{eq} values were analyzed in Fig. 4, activity levels for ^{226}Ra and ^{232}Th were noted to be relatively low and consistent with a few higher outliers for ^{232}Th. Substantial variability's highest median values and widest range were noted for ^{40}K across the cement samples, implying an overall radioactivity dominance. Further observation indicates that a fairly broad spread for Ra_{eq} had so far reflected a combined radiological impact from different sources.

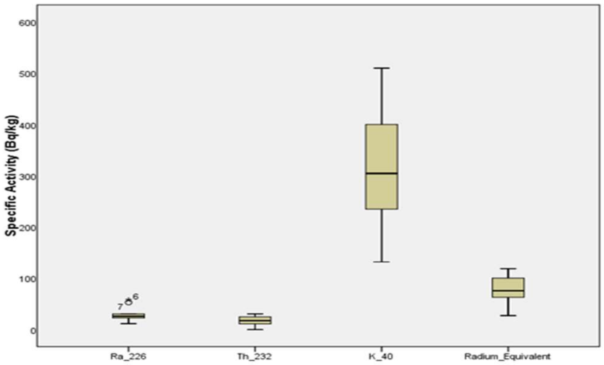

Fig. 4. Distribution and variability for ^{226}Ra, ^{232}Th, ^{40}K, and Ra_{eq}.

Some of the recommended safety limits for the assessed radiological parameters are presented in Table IV.

Table IV: Some of the recommended radiological safety limits [14].

Radionuclides/Radiological Parameter	Recommended values
^{238}U	35 NGy h⁻¹
^{232}Th	30 NGy h⁻¹
^{40}K	400 NGy h⁻¹
Radium equivalent	370 NGy h⁻¹
Absorbed gamma dose rate (DR)	84nGy hr⁻¹
Annual Effective Dose Equivalent (AEDE)	0.46 mSv y⁻¹
Annual gonadal dose equivalent (AGDE)	0.3 mSv y⁻¹
Activity Utilization Index (AUI)	<2
External hazard index (Hex)	≤1
Internal hazard index (Hin)	≤1
Gamma Representative Level Index (RLI)	<1
Excess lifetime cancer risk (ELCR)	0.29×10^{-3}

According to the UNSCEAR recommended safety limits, all calculated indices such as H_{ex}, H_{in}, I_γ, RLI, and I_α must be less than or equal to 1 in their upper limit [14], [16]. For the radiological indices, the calculated mean values were H_{ex} (0.212 ± 0.023), H_{in} (0.293 ± 0.034), I_γ (0.289 ± 0.030), *RLI* (0.579 ± 0.061), and I_α (0.149 ± 0.021). All these values are below the set limit value of 1, indicating that they are not substantially higher than the natural background radiation in the environment [6], [25 - 26]. Thus, the results suggest negligible radiological risk under the assumptions applied to the population and the environment. However, cumulative exposure from multiple building materials may somehow affect the risk of exposure due to relatively higher levels of NORM from some materials.

A similar analysis on distribution and variability using box and whisker plot is provided in Fig. 5 for $H_{ex}, H_{in}, I_\gamma, RLI$, and I_α.

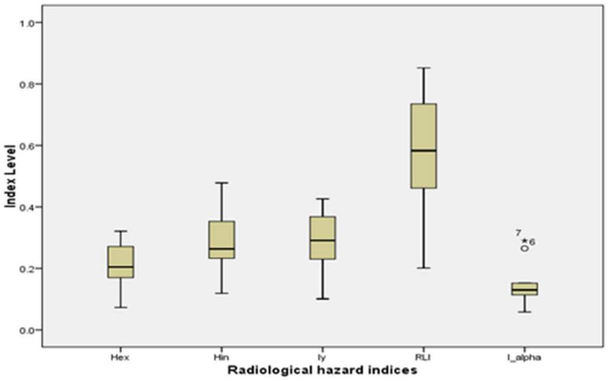

Fig. 5. Distribution and variability $H_{ex}, H_{in}, I_\gamma, RLI$, and I_α.

Fig. 5 shows greater variability for RLI and slight variability for H_{in} as compared to I_γ. While consistent values were observed for H_{ex}, I_α exhibited the least variability, though some outliers were observed beyond the main distribution. Overall, the RLI demonstrated the greatest dominance in both magnitude and variability, whereas the radiological hazard indices generally remained low and below unity ("1") for all cement samples, with only occasional deviations.

C. Dose Assessment

A summary of the calculated mean values for Absorbed Dose Rates (ADR), annual effective dose equivalents (AEDE), Annual Gonad Dose Equivalent (EGDE), and Excess Life Cancer Risks (ELCR) is presented in Table V.

Table V: Calculated ADR, AEDE, AEDE, EGDE, and ELCR.

Radiological Parameter	Mean	UNSCEAR limit
ADR_{Out} (nGy hr⁻¹)	36.2±0.52	<54
ADR_{in} (nGy hr⁻¹)	72.5±7.51	84
$AEDE_{out}$ (mSv y⁻¹)	0.044±0.0046	1
$AEDE_{in}$ (mSv y⁻¹)	0.178±0.019	1
AGDE (mSv y⁻¹)	$(261 \pm 27.06) \times 10^{-3}$	<0.3
$ELCR_{Out}$	$(0.155 \pm 0.016) \times 10^{-3}$	0.29×10^{-3}
$ELCR_{in}$	$(0.622 \pm 0.064) \times 10^{-3}$	1.1×10^{-3}

The mean ADR_{Out} and ADR_{in} were 36.2 ± 8.52 nGy hr^{-1} and 72.5 ± 7.51 nGy hr^{-1}, respectively. Both outdoor and indoor dose rates were less than the global average of 54 nGy hr^{-1} and 84 nGy hr^{-1}, respectively, as reported by various studies, and the UNSCEAR 2008 [13], [41]. Also, mean indoor and outdoor annual effective doses were 0.178 ± 0.019 mSv y^{-1} and 0.044 ± 0.0046 mSv y^{-1}, respectively. AEDE values were also below the recommended limit of 1 mSv y^{-1} and considerably lower than the world average of 0.4 mSv y^{-1} [10], [16]. Calculated mean AGDE value was 261 ± 27.06 x 10^{-3} mSv y^{-1}. The calculated values were also less than the set international limits of 0.3 mSv y^{-1} [14]. Values for ADR, AEDE, and AGDE suggest that these cements pose negligible radiological risks to the population that works and uses these locally produced cements in Malawi based on global reference levels.

Excess Lifetime Cancer Risk (ELCR) represents the probability of an individual developing cancer over a lifetime due to exposure to carcinogenic agents such as ionizing radiation. According to the Linear No-Threshold Model, any amount of ionizing radiation is assumed to carry a proportional risk of inducing cancer and genetic mutations [42]. The scientific community commonly adopts a risk coefficient of 0.05 Sv^{-1}, as recommended by the International Commission on Radiological Protection, implying that approximately 5% of a population exposed to 1 Sv of radiation may develop fatal cancer [28–29], [42].

The computed mean outdoor and indoor ELCR values were 0.155 ± 0.016 x 10^{-3}, and 0.622 ± 0.064 × $10^{-3,}$ respectively, with estimates based on the world average's life expectancy of 70 years. Studies indicate that the recommended outdoor and indoor ELCR safety limits should be 0.29 x 10^{-3} and 1.1 x 10^{-3}, respectively [14], [16]. The values were lower than the set limits, with no considerations on complex parameters such as estimated intakes, exposures, chemical-specific dose, and response data to determine the risk of individuals over such a lifetime [25]. Thus, the likelihood of cements causing radiation-induced risks such as cancer in the population over one's lifetime is therefore minimal. These findings are also in agreement with other studies conducted worldwide, such as [3], [4], [16], [35].

Statistical analysis revealed that the median values of NORM and the associated radiological parameters evaluated in this study did not exceed the safety limits recommended by UNSCEAR ($p > 0.05$). Therefore, there was insufficient statistical evidence to reject the null hypothesis, indicating that the measured radiological parameters remained within internationally accepted safety limits. Furthermore, the median activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K did not differ significantly among the analyzed cement samples based on the Sign test and Kruskal–Wallis test results. Consequently, the study found no statistical evidence of elevated NORM levels in the investigated cement products.

Although the study provides important baseline information on the radiological characteristics of cement produced in Malawi, several limitations should be acknowledged. The use of purposive sampling, while effective for selecting samples relevant to the study objectives and improving data reliability [43], may introduce selection bias. In particular, cement brands that were more accessible, affordable, or widely distributed by local suppliers were more likely to be included in the analysis. In addition, the relatively small sample size limited the extent to which the full variability of cement products available in the country could be captured. Since samples were collected from selected districts rather than all regions of Malawi, the findings may not fully represent nationwide variations in cement availability and usage patterns. Therefore, the results should be interpreted with caution, and further studies involving larger and more geographically representative sample sets are recommended to validate and expand upon the present findings.

IV. CONCLUSION

Natural occurring radionuclides, namely ^{226}Ra, ^{232}Th, and ^{40}K, were assessed in all cement brands produced and used as building materials in Malawi using HPGe gamma-ray spectrometry. The mean activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K was found to be below the internationally recommended reference limits, with ^{40}K exhibiting dominant activities, consistent with the typical trend observed in environmental samples. Other radiological parameters, such as dose rates, radium equivalent, external and internal hazard index, yearly effective doses, excess life cancer risk, annual gonadal dose equivalent, and the alpha index, were also estimated.

The results obtained for all assessed parameters were below the global average values and international safety limits recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation and the International Commission on Radiological Protection. This indicates that the cement brands locally produced and utilized in Malawi pose negligible radiological risk to both the population and the environment. Furthermore, the probability of long-term health effects, such as cancer development over a lifetime, is considered minimal. These findings are in agreement with similar studies conducted in other parts of the world. Nevertheless, the observed variations in activity concentrations among the cement samples underscore the importance of periodic monitoring and assessment of naturally occurring radioactive materials (NORM) in cement. Future studies should also investigate radioactivity levels in other building materials used in Malawi in order to comprehensively evaluate their potential radiological impact on the public and the environment.

References

[1] A. Coulibaly, F. Nafogou, B. Kone, A. Dicko, and O. Camara, "Assessment of natural radioactivity in cements (local and imported) in Mali," Radiation

Science and Technology, vol. 10, no. 3, pp. 37–42, 2024, doi: 10.11648/j.rst.20241003.11.

[2] S. Degra et al., “Assessment of natural radioactivity and associated radiological hazards in cement used as a building material in Rajasthan, India,” Environmental Claims Journal, pp. 1–26, 2025, doi: 10.1080/10406026.2025.2548517.

[3] A. H. E. Salama, M. Abdallah, S. Alameer, and W. R. A. Tamimi, “Performance, measurements and potential radiological risks of natural radioactivity in cements used in Jordan,” Jordan Journal of Civil Engineering, vol. 16, no. 1, 2022.

[4] T. Abate, “Radioactivity and health risk assessments in cement samples commonly used as construction materials in the case of South Gondar Zone, Ethiopia,” EPJ Nuclear Sciences & Technologies, vol. 8, p. 13, 2022, doi: 10.1051/epjn/2022012.

[5] A. Eštoková and L. Palaščáková, “Assessment of natural radioactivity levels of cements and cement composites in the Slovak Republic,” International Journal of Environmental Research and Public Health, vol. 10, no. 12, pp. 7165–7179, 2013, doi: 10.3390/ijerph10127165.

[6] T. E. Adreani, E. Mattar, K. Alsafi, A. Sulieman, and I. I. Suliman, “Natural radioactivity and radiological risk parameters in local and imported building materials used in Sudan,” Applied Ecology and Environmental Research, vol. 18, no. 6, pp. 7563–7572, 2020, doi: 10.15666/aeer/1806_75637572.

[7] V. A. P. de Aguiar, N. H. Medina, M. A. G. da Silveira, and R. H. Moreira, “Gamma-ray doses proceedings from naturally occurring radionuclides in closed environments.” 2009 International Nuclear Atlantic Conference - INAC 2009, Rio de Janeiro, RJ, Brazil, September 27 to October 2, 2009. ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN.

[8] A. K. Ademola, O. P. Abodunrin, M. A. Fatai, and J. O. Omoboyede, “Assessment of natural radioactivity levels in cement samples commonly used for construction in Lagos and Ogun State, Nigeria,” Elixir Nuclear and Radiation Physics, vol. 104, pp. 44416–44420, 2017.

[9] N. Alkhomashi et al., “Assessment of radioactivity and trace elements of cement produced in Saudi Arabia,” Environmental Earth Sciences, vol. 76, no. 7, p. 280, 2017, doi: 10.1007/s12665-017-6605-x.

[10] M. M. Alonso et al., “Data on natural radionuclides’ activity concentration of cement-based materials,” Data in Brief, vol. 33, p. 106488, 2020, doi: 10.1016/j.dib.2020.106488.

[11] Y. A. Raham and H. D. Al-Attabi, “Study and calculation of the specific natural radioactivity of samples of Portland cement in Iraq using a high-purity germanium detector,” Nexo Revista Científica, vol. 36, no. 6, pp. 1141–1149, 2023, doi: 10.5377/nexo.v36i06.17470.

[12] A. Baha et al., “Radioactivity in decorative building materials: Insights from Johor, Malaysia,” Radiation Physics and Chemistry, vol. 209, p. 111006, 2023, doi: 10.1016/j.radphyschem.2023.111006.

[13] UNSCEAR, Sources and Effects of Ionizing Radiation: UNSCEAR 2008 Report to the General Assembly with Scientific Annexes A and B. New York, NY, USA: United Nations, 2010.

[14] E. Devanesan et al., “Natural radioactivity concentrations and dose assessment in coastal sediments along the east coast of Tamilnadu, India with statistical approach,” Acta Ecologica Sinica, vol. 40, no. 5, pp. 353–362, 2020, doi: 10.1016/j.chnaes.2019.06.001.

[15] S. Lewicka, B. Piotrowska, A. Łukaszek-Chmielewska, and T. Drzymała, “Assessment of natural radioactivity in cements used as building materials in Poland,” International Journal of Environmental Research and Public Health, vol. 19, no. 18, p. 11695, 2022, doi: 10.3390/ijerph191811695.

[16] M. Waseem et al., “Evaluation of radiation rates and health hazards from different cement types in Pakistan,” Atmosphere, vol. 15, no. 11, p. 1393, 2024, doi: 10.3390/atmos15111393.

[17] K. Mtei, A. Amasi, J. Ijumba, N. D. Chau, and P. Jodłowski, “Natural radioactivity in Tanzania cements and their raw materials,” Research Journal of Environmental and Earth Sciences, vol. 6, no. 10, pp. 469–474, 2014.

[18] N. Sharma, J. Singh, S. C. Esakki, and R. M. Tripathi, “A study of the natural radioactivity and radon exhalation rate in some cements used in India and its radiological significance,” Journal of Radiation Research and Applied Sciences, vol. 9, no. 1, pp. 47–56, 2016, doi: 10.1016/j.jrras.2015.09.001.

[19] I. Kafodya, D. Basuroy, J. M. Marangu, G. Kululanga, R. Maddalena, and V. I. Novelli, “Mechanical performance and physico-chemical properties of limestone calcined clay cement (LC3) in Malawi,” Buildings, vol. 13, no. 3, p. 740, 2023, doi: 10.3390/buildings13030740.

[20] C. C. Kaonga, I. B. M. Kosamu, and W. R. Utembe, “A review of metal levels in urban dust, their methods of determination, and risk assessment,” Atmosphere, vol. 12, no. 7, p. 891, 2021, doi: 10.3390/atmos12070891.

[21] C. C. Utsale, C. C. Kaonga, F. G. D. Thulu, P. Chiipa, S. James, and I. B. M. Kosamu, “Source apportionment and risk assessment of heavy metals in soils during dry and rainy seasons in Southern Malawi,” Pollutants, vol. 5, no. 1, p. 6, 2025, doi: 10.3390/pollutants5010006.

[22] Z. Vidrova, “Supply chain management in the aspect of globalization,” SHS Web of Conferences, vol. 74, p. 04031, 2020, doi: 10.1051/shsconf/20207404031.

[23] Ministry of Finance and Economic Affairs, Government of Malawi, Annual Economic Report 2022. Lilongwe, Malawi: Department of Economic

Planning and Development, 2022.

[24] G. Licitra, G. D'Amore, and M. Magnoni, Physical Agents in the Environment and Workplace: Noise and Vibration. Boca Raton, FL, USA: CRC Press, 2020.

[25] S. Nemlioglu, N. Sezgin, and B. Ozdogan Cumali, "Natural radioactivity in cement," in Advances in the Toxicity of Construction and Building Materials. Amsterdam, Netherlands: Elsevier, 2022, pp. 171–206. doi: 10.1016/B978-0-12-824533-0.00005-0.

[26] V. Vineethkumar, C. S. Kaliprasad, and V. Prakash, "Assessment of natural radioactivity and radiation index parameters in the coastal environment of Kerala," Radiation Protection and Environment, vol. 41, no. 2, pp. 99–103, 2018, doi: 10.4103/rpe.RPE_14_18.

[27] M. Salman, "Radiation hazard index of common imported ceramics used for building materials in Iraq," Australian Journal of Basic and Applied Sciences, vol. 11, no. 10, pp. 94–102, 2017.

[28] ICRP, "The 2007 recommendations of the International Commission on Radiological Protection," Annals of the ICRP, vol. 37, nos. 2–4, pp. 1–332, 2007, doi: 10.1016/j.icrp.2007.10.003.

[29] D. R. Fisher and F. H. Fahey, "Appropriate use of effective dose in radiation protection and risk assessment," Health Physics, vol. 113, no. 2, pp. 102–109, 2017, doi: 10.1097/HP.0000000000000674.

[30] M. A. Pashazadeh, M. Aghajani, I. Nabipour, and M. Assadi, "Annual effective dose from environmental gamma radiation in Bushehr City," Journal of Environmental Health Science and Engineering, vol. 12, no. 1, p. 4, 2014, doi: 10.1186/2052-336X-12-4.

[31] F. O. Ugbede and E. O. Echeweozo, "Estimation of annual effective dose and excess lifetime cancer risk from background ionizing radiation levels within and around quarry site in Okpoto-Ezillo, Ebonyi State, Nigeria," Journal of Environment and Earth Sciences, vol. 7, no. 12, 2017.

[32] A. A. Ridha and H. A. Hasan, "Cancer risk due to the natural radioactivity in cigarette tobacco," Detection, vol. 4, no. 3, pp. 54–65, 2016, doi: 10.4236/detection.2016.43008.

[33] T. W. MacFarland and J. M. Yates, "Sign test," in Introduction to Nonparametric Statistics for the Biological Sciences Using R. Cham, Switzerland: Springer, 2016, pp. 51–76. doi: 10.1007/978-3-319-30634-6_2.

[34] A. A. Elewee, M. S. Alsaffar, S. F. Alhous, and M. S. Aswood, "Evaluating the level of ^{226}Ra, ^{232}Th and ^{40}K in different building materials," Nuclear Analysis, vol. 4, no. 1, p. 100158, 2025, doi: 10.1016/j.nucana.2025.100158.

[35] M. Aslam, R. Gul, T. Ara, and M. Hussain, "Assessment of radiological hazards of naturally occurring radioactive materials in cement industry," Radiation Protection Dosimetry, vol. 151, no. 3, pp. 483–488, 2012, doi: 10.1093/rpd/ncs018.

[36] A. Kadum, A. H. Bensaoula, and B. Dahmani, "Measurement of natural radioactivity in cement of Tlemcen-Algeria using a well-shape NaI(Tl) detector," Journal of Natural Sciences Research, vol. 3, no. 13, pp. 182–191, 2013.

[37] D. Shahbazi-Gahrouei, M. Gholami, and S. Setayandeh, "A review on natural background radiation," Advanced Biomedical Research, vol. 2, no. 1, p. 65, 2013, doi: 10.4103/2277-9175.115821.

[38] F. Shala et al., "Natural radioactivity in cements and raw materials used in Albanian cement industry," Environmental Earth Sciences, vol. 76, no. 20, p. 670, 2017, doi: 10.1007/s12665-017-7014-x.

[39] O. Ndour et al., "Assessment of natural radioactivity and its radiological hazards in several types of cement used in Senegal," SN Applied Sciences, vol. 2, no. 12, p. 2078, 2020, doi: 10.1007/s42452-020-03904-7.

[40] M. E. Farid, A. Abd El-Mageed, E. Saleh, M. Mansour, and A. Mohammed, "Assessment of natural radioactivity and the associated hazards in some local cement types used in Yemen," Radiation Protection and Environment, vol. 36, no. 1, p. 27, 2013, doi: 10.4103/0972-0464.121821.

[41] O. E. Esi, G. O. Avwiri, O. A. Sylvanus, and D. C. Onwudiwe, "Radiometric survey of sediments and health risk assessments from the southern coastal area of Delta State, Nigeria," Heliyon, vol. 10, no. 5, p. e26805, 2024, doi: 10.1016/j.heliyon.2024.e26805.

[42] M. Doss, "Facilitating the end of the linear no-threshold model era," Journal of Nuclear Medicine, vol. 65, no. 8, pp. 1173–1174, 2024, doi: 10.2967/jnumed.123.267868.

[43] S. Campbell et al., "Purposive sampling: Complex or simple? Research case examples," Journal of Research in Nursing, vol. 25, no. 8, pp. 652–661, 2020, doi: 10.1177/1744987120927206.