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Determination of natural radioactivity and the associated radiation hazards in building materials used in Polur, Tiruvannamalai District, Tamilnadu, India using gamma ray spectrometry with statistical approach

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ABSTRACT

The natural radioactivity in building materials collected from Polur, Tamilnadu has been determined using gamma ray spectrometer. The radiological parameters such as radium equivalent activity (Ra_{eq}), absorbed dose rate (D_R), annual effective dose rate (H_R), alpha index (I_α), gamma-index (I_γ), internal (H_{in}) and external hazard indices (H_{ex}) were evaluated to assess the radiation hazard for people dwelling in the study area. The calculated radiological parameters were taken for multivariate statistical analysis to study the relation between radionuclides and radiological parameters. The values obtained in the study are within the recommended safety limits, showing that these building materials do not pose any significant radiation hazard and hence the use of these materials in the construction for dwelling purpose can be considered to be safe for the inhabitants.

1. Introduction

The building materials derived from rocks and soils, which always contain natural radionuclides of Uranium (^{238}U), and Thorium (^{232}Th) series, and the radioactive isotope of Potassium (^{40}K), gives both external and internal radiation exposure to the inhabitants of dwellings built with such materials. The gamma radiation arising from the walls, floors and ceilings, and radon and thoron and their progeny are the major sources of radiation exposures. As individuals spend more than 80% of their time indoors the internal and external radiation exposures from building materials create prolonged exposure situations (Stoulos et al., 2003). The absolute and relative concentrations of *U*, *Th* and *K* in construction materials can vary dramatically depending on source (Faul, 1954).

The knowledge of natural radioactivity levels is useful in order to set the standards and national guidelines in the light of international recommendations. Due to the increasing social concern, a large number of research groups are engaged in the measurement of natural radioactivity on national as well as worldwide levels (Bou-Rabee and Bem, 1996; Giuseppe et al., 1996; Muhammad et al., 2001; Kovler et al., 2002; Ahmed, 2005; Ngachin et al., 2006; Oktay Baykara et al., 2011). Natural radioactivity in some Indian building materials has also been reported by some authors (Nageswara Rao et al., 1996; Kumar et al., 1999, 2003; Ravisankar et al., 2012). However detailed information of each state is scanty. The data regarding the concentration of ^{226}Ra, ^{232}Th and ^{40}K in building materials belonging to Polur of Tiruvannamalai District, Tamilnadu state of India is not available in literature.

The prime objective of this work is to develop reference data of natural radioactive elements for the building materials of the area under investigation, and to evaluate their radiological consequence if used as building materials.

In this work are presented the results of the measurements of ^{226}Ra, ^{232}Th and ^{40}K concentrations in twenty eight building materials of five types of samples that are used commonly in Polur Tamilnadu, India using gamma-ray spectrometry. The potential radiological hazards associated to these materials were calculated such as radium equivalent activity (Ra_{eq}), absorbed gamma dose rate (D_R), annual effective dose rate (H_R), alpha index ((I_α), gamma index (I_γ), external hazard (H_{ex}) and internal hazard (H_{in}) indexes. The obtained results were compared with the recommended permissible limits.

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2. Materials and methods

2.1. Sampling and preparation

Samples representing five different commonly used structural and covering building materials were collected randomly from sites where housing and other buildings were under construction and from building material suppliers in Polur town for the measurement of the specific radioactivity of ^{226}Ra, ^{232}Th and ^{40}K. Structural building materials (cement, brick, clay, sand and soil) are used in bulk amounts.

The collected samples were kept in polyethylene bags which were numbered and cataloged for identification. The samples were brought to the sample preparation section of the low-level activity measurement laboratory. The brick samples were crushed, ground, and pulverized to powder. The powder was passed through a sieve of 200 μm mesh size. The samples in powder form were dried at 110 °C in a temperature-controlled furnace until there was no detectable change in the mass of the sample. The samples were transferred to radon-impermeable plastic containers of 6 cm diameter and 6.5 cm height. Their respective net weights were measured and recorded with a highly sensitive balance. Then these samples were sealed and left air-tight for four weeks to allow for radium and its short progeny to be in radioactive equilibrium.

2.2. Gamma spectrometric analyses of samples

A 3″ × 3″ NaI (Tl) scintillation detector has been used for spectral measurements to enable one to cover the energy spectrum of the naturally occurring radionuclides up to 2.6 MeV (^{208}Tl, a daughter product of ^{232}Th). The detector is shielded by 15 cm thick lead on all sides including top to reduce background due to cosmic ray component by almost 98%. The inner sides of the lead shielding is lined with 2 mm thick Aluminum. Standard sources of the primordial radionuclides obtained from IAEA in the same geometry and having the same density, as that of the prepared soil samples, were used to determine the efficiency of the detector for various energies in the prescribed geometry. The prepared samples were placed on top of the 3″ × 3″ NaI (Tl) detector. Using the gamma ray spectrometer and multichannel analyzer, count spectra were obtained for each of the building material sample. The activity content of the three primordial radionuclides viz., ^{40}K, ^{232}Th and ^{238}U are deduced from the count spectra. The regions under the peaks corresponding to 1.46 MeV (^{40}K), 1.764 MeV (^{214}Bi) and 2.614 MeV (^{208}Tl) energies were considered to arrive at the radioactivity levels of ^{40}K, ^{238}U and ^{232}Th, respectively. The minimum detectable activity (MDA) of each of the three primordial radionuclides was determined from the background radiation spectrum obtained for the same counting time as was done for the soil samples and are given as 2.15 Bq kg^{-1} for ^{232}Th, 2.22 Bq kg^{-1} for ^{238}U and 8.83 Bq kg^{-1} for ^{40}K. The sealed containers were left for at least 4 weeks (>7 half life's ^{222}Rn) before counting by gamma ray spectrometry in order to ensure that the daughter products of ^{226}Ra up to ^{210}Pb and ^{228}Th up to ^{208}Pb achieve equilibrium with their respective parent radionuclides. All the building materials were subjected to gamma ray spectral analysis with a counting time of 20,000 s.

2.3. Statistical analysis of radioactive data

In this present work, radioactive data were analyzed by different statistical analyses (Pearson, principal component and cluster analysis) to draw valid conclusions regarding the nature and significance of the radioactive-element distribution in the building materials of Polur, Tamilnadu, India. The main statistical software "Statistical Program for the Social Science" (SPSS 16.0/PC) was used to perform the statistical analysis.

3. Results and discussion

3.1. Determination of radionuclides in the building materials

The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K and mean value of activity concentrations have been calculated for all the samples are given in Table 1. The mean value was calculated depending on the number of BDL (below detection limit) values in the data set. If number of BDL values are <15%, all the BDL values are replaced by MDA/2, where (MDA-Minimum detectable activity). If the numbers of BDL values are between 15 to 50% of the data set, mean value was arrived at by trimmed mean method. In present study Geometrical mean values are tabulated. As shown in the Table 1, the activity concentration in building materials varied from ≤2.22 (BDL) to 88.46 Bq kg^{-1} for ^{226}Ra with a geometrical mean value of 9.19 Bq kg^{-1}. For ^{232}Th the values varied from 24.56 to 358.6 Bq kg^{-1} with a geometrical mean value of 45.60 Bq kg^{-1} and for ^{40}K the values varied from 103.43 to 633.94 Bq kg^{-1} with a geometrical mean value of 295.11 Bq kg^{-1}. The obtained results indicate that the average specific activity for all the studied building materials is less than world average values of 500 and 50 Bq kg^{-1} for ^{40}K and ^{226}Ra, respectively whereas the average specific activity exceeds the corresponding value of 50 Bq kg^{-1} for ^{232}Th (NEA-OECD, 1979; UNSCEAR, 1993). Fig. 1 shows the variation of activity concentrations with building materials of Polur, Tamilnadu.

3.2. Radium equivalent activity (Ra_{eq})

To represent the activity levels of ^{226}Ra, ^{232}Th and ^{40}K by a single quantity, which takes into account the radiation hazards associated with them, a common radiological index has been introduced. This index is called radium equivalent (Ra_{eq}) activity and is mathematically defined by Beretka and Mathew (Beretka and Mathew, 1985)

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (1)$$

where A_{Ra}, A_{Th}, A_K represents the activity concentration of ^{226}Ra, ^{232}Th and ^{40}K. In the above relation, it has been assumed that 10 Bq kg^{-1} of ^{226}Ra, 7 Bq kg^{-1} of ^{232}Th and 130 Bq kg^{-1} of ^{40}K produce equal γ-dose. The maximum dose of Ra_{eq} in building materials must be less than 370 Bq kg^{-1} for safe use, i.e., to keep the external dose below 1.5 mGy year^{-1}(Beretka and Mathew, 1985). As can be seen from Table 2, for all materials except for the sand studied, the Ra_{eq} values are well below the upper limit. Fig. 1 shows the variation of radium equivalent activity with building materials of Polur, Tamilnadu.

3.3. Estimation of the absorbed dose rate (D_R) and annual effective dose rate (AEDR)

The absorbed dose rates due to γ - radiations in air at one meter above the ground surface for the uniform distribution of the naturally occurring radionuclides (^{226}Ra, ^{232}Th and ^{40}K) were calculated based on guidelines provided by UNSCEAR (1993). We assumed that the contributions from other naturally occurring radionuclides, such as ^{235}U, ^{87}Rb, ^{138}La, ^{147}Sm and ^{178}Lu, to actual dose rates are insignificant. The conversion factors used to compute absorbed γ-dose rate (D) in air per unit activity concentration in Bq kg^{-1} (dry weight) corresponds to 0.462 nGy h^{-1} for ^{226}Ra (of uranium series), 0.604 nGy h^{-1} for ^{232}Th and 0.0417 nGy h^{-1} for ^{40}K. Therefore, D_R can be calculated by UNSCEAR (2000)

$$D_R = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K. \quad (2)$$

To estimate the annual external effective dose rates, the conversion coefficient from absorbed dose in air to effective dose (0.7 SvGy^{-1})and outdoor occupancy factor (0.2) proposed by UNSCEAR (2000) are used.

Table 1
Activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in building materials of Polur, Tiruvannamalai District, Tamilnadu, India.

Sample ID	Materials	Activity concentration (Bq kg^{-1})		
		^{226}Ra	^{232}Th	^{40}K
PBI	Brick-1	10.9 ± 6.15	33.99 ± 5.45	440.34 ± 30.59
PB2	Brick-2	9.83 ± 6.75	36.45 ± 6.02	379.67 ± 32.61
PB3	Brick-3	6.75 ± 5.81	48.34 ± 5.41	344 ± 27.86
PB4	Brick-4	6.87 ± 6.18	50.44 ± 5.75	444.89 ± 30.46
PB5	Brick-5	6.49 ± 6.07	39.35 ± 5.54	325.87 ± 29.05
PB6	Brick-6	11.1 ± 6.30	46.7 ± 5.74	330.99 ± 29.78
PB7	Brick-7	10.72 ± 6.69	69.58 ± 6.32	379.24 ± 31.44
PB8	Brick-8	6.51 ± 6.28	43.22 ± 5.77	276.05 ± 29.38
PC1	Clay-1	7.76 ± 6.94	45.04 ± 6.33	332.03 ± 32.81
PC2	Clay-2	9.71 ± 6.46	43.83 ± 5.87	287.84 ± 30.15
PC3	Clay-3	4.84 ± 5.98	37.32 ± 5.47	350.08 ± 29.06
PC4	Clay-4	8.16 ± 6.80	34.45 ± 6.07	386.06 ± 33.04
PC5	Clay-5	BDL	42.4 ± 5.71	343.34 ± 29.59
PC6	Clay-6	BDL	43.8 ± 6.20	362.65 ± 32.19
PC7	Clay-7	BDL	51.17 ± 5.95	396.12 ± 30.58
PC8	Clay-8	BDL	32.9 ± 6.13	486.52 ± 34.12
PS01	Soil-1	88.46 ± 6.29	39.74 ± 5.76	343.68 ± 30.29
PS02	Soil-2	6.62 ± 7.35	62.98 ± 6.90	261.4 ± 33.42
PS03	Soil-3	7.37 ± 6.29	48.2 ± 5.81	353 ± 30.06
PS04	Soil-4	BDL	60.06 ± 6.79	357.5 ± 33.78
PSA1	Sand	BDL	358.56 ± 10.78	633.94 ± 41.73
CMT1	Cement-1	36.57 ± 7.81	49.62 ± 6.60	201.76 ± 34.12
CMT2	Cement-2	36.99 ± 7.66	41.29 ± 6.36	147.54 ± 33.03
CMT3	Cement-3	37.76 ± 7.94	39.51 ± 6.55	116.62 ± 33.89
CMT4	Cement-4	49.35 ± 8.11	42.36 ± 6.53	113.43 ± 34.21
CMT5	Cement-5	11.2 ± 6.80	24.56 ± 5.87	134.84 ± 30.33
CMT6	Cement-6	28.61 ± 6.32	23.47 ± 6.00	180.73 ± 27.91
CMT7	Cement-7	31.26 ± 6.40	41.75 ± 6.19	233.92 ± 29.15
Geometric mean		9.19	45.60	295.11

Therefore, the effective dose rate in units of mSv year^{-1} has been calculated by the following formula:

$$\text{Annual effective dose rate} = D_R \times 8760\ \text{h y}^{-1} \times 0.7\text{Sv Gy}^{-1} \times 10^{-6} \times 0.8 = D_R \times 4.90 \times 10^{-3}. \quad (3)$$

The calculated gamma dose rate values are presented in Table 2. As given in Table 2, the results of estimated absorbed gamma dose rate in air from building materials varies from 25.63 nGy h^{-1} to 243 nGy h^{-1} with the mean of 53.50 nGy h^{-1}. The estimated mean value of D_R in the studied samples is lower than the world average (populated-weighted) indoor absorbed gamma dose rate of 84 nGy h^{-1}. Hence, these building materials are safe for construction of buildings. Fig. 2 shows the variation of absorbed dose rate with building materials.

In the present study, the annual effective dose rate varies from 0.126 mSv year^{-1} to 1.191 mSv year^{-1} with an average of

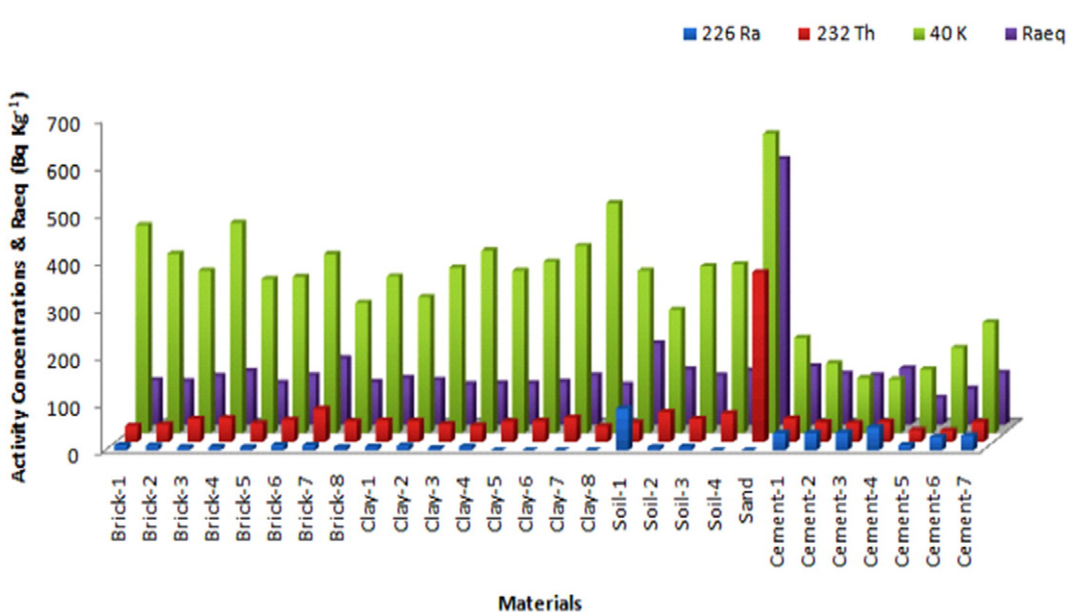

Fig. 1. Shows the variation of activity concentration and radium equivalent activity (Bq kg^{-1}) in building materials of Polur, Tiruvannamalai District, Tamilnadu.

Table 2
Calculated radiological parameters for building materials used in Polur, Tiruvannamalai District, Tamilnadu, India.

Sample ID	Materials	Ra_{eq} (Bq kg^{-1})	D_R (nGy h^{-1}	AEDR (mSv year^{-1})	I_α	I_γ	H_{in}	H_{ex}	AGDE (mSv year^{-1})	ELCR $\times 10^{-3}$	RLI (Bq kg^{-1})	AUI
PBI	Brick-1	93.41	43.92	0.215	0.055	0.353	0.282	0.253	312.26	0.357	0.706	0.481
PB2	Brick-2	91.19	42.38	0.208	0.049	0.342	0.273	0.247	300.43	0.343	0.683	0.486
PB3	Brick-3	102.36	46.66	0.229	0.034	0.379	0.295	0.277	329.55	0.374	0.757	0.556
PB4	Brick-4	113.26	52.19	0.256	0.034	0.423	0.324	0.307	369.98	0.42	0.846	0.585
PB5	Brick-5	87.85	40.35	0.198	0.032	0.327	0.255	0.238	285.55	0.325	0.654	0.468
PB6	Brick-6	103.37	47.13	0.231	0.056	0.381	0.309	0.28	332.11	0.378	0.761	0.592
PB7	Brick-7	139.42	62.79	0.308	0.054	0.51	0.405	0.378	441.53	0.504	1.02	0.803
PB8	Brick-8	89.57	40.62	0.199	0.033	0.33	0.259	0.243	286.35	0.325	0.659	0.5
PC1	Clay-1	97.73	44.63	0.219	0.039	0.362	0.285	0.265	315.17	0.357	0.723	0.537
PC2	Clay-2	94.55	42.96	0.211	0.049	0.347	0.282	0.256	302.44	0.346	0.694	0.545
PC3	Clay-3	85.16	39.37	0.193	0.024	0.319	0.243	0.231	279.47	0.315	0.638	0.432
PC4	Clay-4	87.15	40.67	0.199	0.041	0.328	0.257	0.236	288.89	0.329	0.656	0.448
PC5	Clay-5	87.07	39.92	0.196	0.005	0.326	0.235	0.236	283.66	0.318	0.652	0.419
PC6	Clay-6	90.56	41.57	0.204	0.005	0.34	0.245	0.245	295.5	0.332	0.679	0.434
PC7	Clay-7	103.67	47.42	0.232	0.005	0.388	0.28	0.281	336.68	0.378	0.775	0.505
PC8	Clay-8	84.51	40.15	0.197	0.005	0.327	0.228	0.229	288.34	0.322	0.653	0.343
PS01	Soil-1	171.75	79.2	0.388	0.442	0.608	0.703	0.465	545.99	0.658	1.216	1.463
PS02	Soil-2	116.81	51.99	0.255	0.033	0.424	0.333	0.316	364.74	0.413	0.848	0.683
PS03	Soil-3	103.48	47.23	0.231	0.037	0.383	0.299	0.28	333.67	0.378	0.766	0.563
PS04	Soil-4	113.41	51.18	0.251	0.005	0.419	0.306	0.307	361.87	0.406	0.838	0.584
PSA1	Sand	561.55	243	1.191	0.005	2.004	1.516	1.522	1695.3	1.918	4.008	3.365
CMT1	Cement-1	123.06	55.27	0.271	0.183	0.437	0.431	0.333	382.95	0.448	0.874	0.916
CMT2	Cement-2	107.4	48.18	0.236	0.185	0.388	0.396	0.296	332.62	0.392	0.757	0.84
CMT3	Cement-3	103.24	46.17	0.226	0.189	0.362	0.381	0.279	317.98	0.378	0.724	0.83
CMT4	Cement-4	118.66	53.11	0.26	0.247	0.414	0.454	0.321	364.71	0.434	0.828	0.996
CMT5	Cement-5	56.7	25.63	0.126	0.056	0.205	0.183	0.153	179.06	0.206	0.41	0.373
CMT6	Cement-6	76.08	34.93	0.171	0.143	0.273	0.253	0.206	242.53	0.283	0.545	0.577
CMT7	Cement-7	108.97	49.41	0.242	0.156	0.391	0.379	0.294	343.62	0.399	0.781	0.782
Average		118.28	53.50	0.26	0.08	0.43	0.36	0.32	375.46	0.43	0.86	0.72

Ra_{eq}—radium equivalent activity; D_R—absorbed dose rate; AEDR—annual effective dose rate; I_α—alpha index; I_γ—gamma index;
H_{in}—internal hazard index; H_{ex}—external hazard index; AGDE—annual gonadal dose equivalent; ELCR—excess life time cancer;
RLI—representative level index; AUI—activity utilization index.

0.260 mSv year^{-1}. In normal background areas, the average annual external effective dose from terrestrial radionuclides is 0.46 mSv year^{-1} (UNSCEAR, 1993). The estimated mean value of annual effective dose is 0.260 mSv year^{-1}. Therefore, the obtained mean value from this study is lower than recommended value. This result reflects the building materials do not pose any significant radiation hazards. Fig. 3 shows the variation of annual effective dose rate with building materials of Polur, Tamilnadu.

3.4. Annual gonadal dose equivalent (AGDE)

In the same context, the activity of bone narrow and bone surface cells are considered to be organs of interest by UNSCEAR (1988). Therefore, the annual gonadal dose equivalent (AGDE) arising from the specific activities of ^{226}Ra, ^{232}Th and ^{40}K was calculated using the following formula (Mamont-Ciesla et al., 1982):

$$AGDE = 3.09\, A_{Ra} + 4.18\, A_{Th} + 0.31 A_K. \tag{4}$$

The AGDE values are presented in Table 2. The average values do not generally exceed the permissible recommended limits, indicating that the hazardous effects of the radiation are negligible. However, the overall average AGDE value is found to be 375.46 mSv year^{-1}. In the literature, the average AGDE value for the Eastern Desert of Egypt was found to be 2398 mSv year^{-1} (Arafa, 2004) and world average value is 0.3 mSv year^{-1} (Xinwei et al., 2006). The AGDE values of Polur

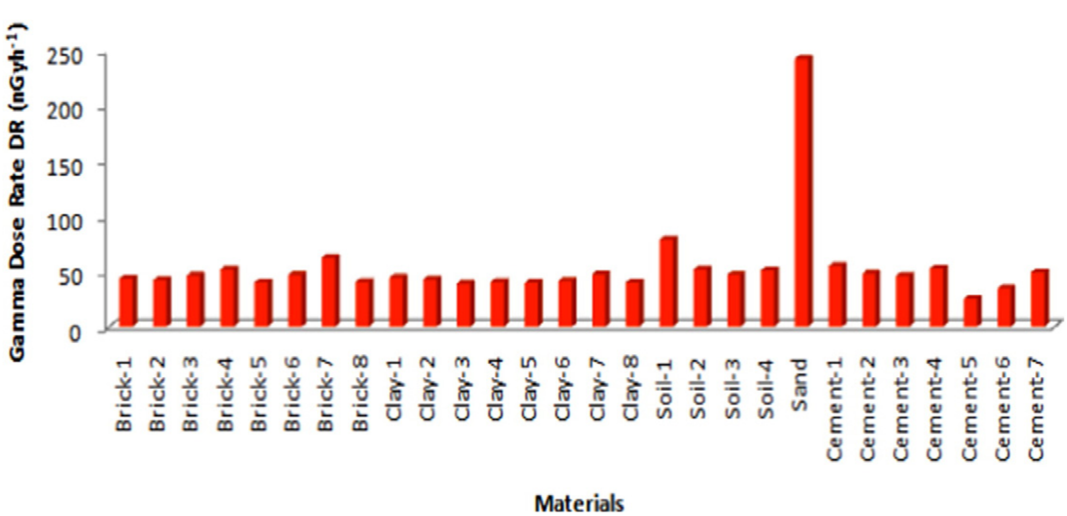

Fig. 2. Shows the variation of gamma dose rate (nGy h^{-1})) in building materials of Polur, Tiruvannamalai District, Tamilnadu.

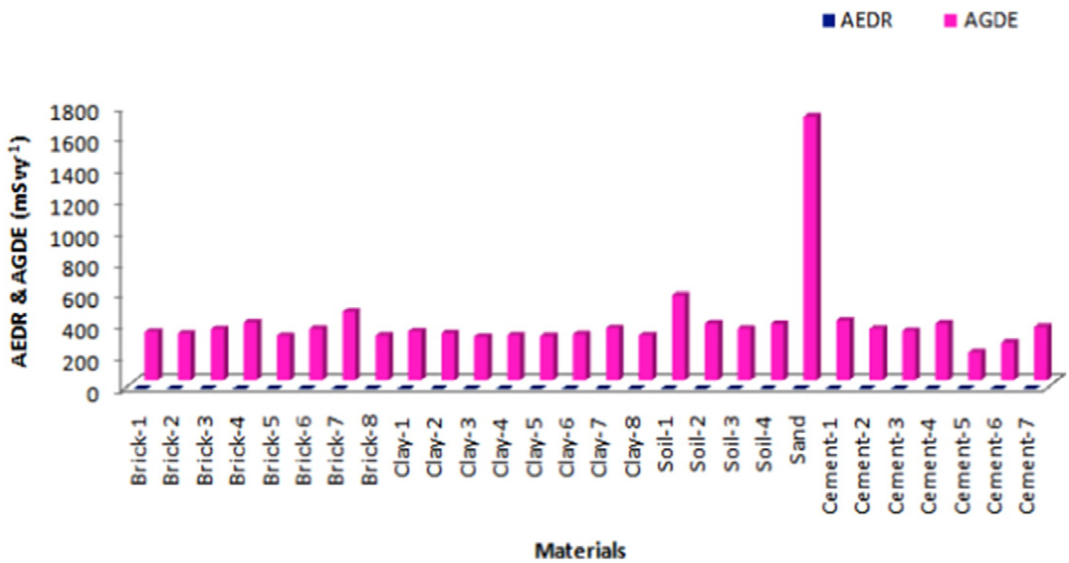

Fig. 3. Shows the variation of annual effective dose rate and AGDE (mSv year^{-1})) in building materials of Polur, Tiruvannamalai District, Tamilnadu.

building material showed higher than Eastern Desert of Egypt whereas lower than the world average value. Fig. 3 shows the variation of annual gonadal dose equivalent (AGDE) with building materials of Polur, Tamilnadu.

3.5. Assessment of radiological hazards

Four indexes are used in this paper for assessment of excess gamma radiation from the building materials in order to be ensuring of the safety of building material usage.

(i) Alpha index (I_α) (ii) Gamma index (I_γ)
(iii) Internal hazard index (H_{in}) (iv) External hazard index (H_{ex}).

3.5.1. Alpha index (I_α)

The excess alpha radiation due to radon inhalation originating from building materials is assessed through the alpha index, which is defined as follows (Righi and Bruzzi, 2006)

$$I_\alpha = \frac{A_{Ra}}{200\ \text{Bq kg}^{-1}}. \quad (5)$$

The recommended exemption level and recommended upper level of ^{226}Ra activity concentrations are 100 Bq kg^{-1} and 200 Bq kg^{-1}, respectively, in building materials as suggested in many countries of the world (RPAD, 2000). When the ^{226}Ra activity concentration of a building material exceeds the value of 200 Bq kg^{-1}, it is possible that radon exhalation from this material could cause indoor radon concentrations exceeding 200 Bq m^{-3}. On the other hand (RPAD, 2000), when the ^{226}Ra activity concentration is below 100 Bq kg^{-1}, then radon exhalation from the building materials could not cause indoor radon concentrations exceeding 200 Bq m^{-3}. These considerations are reflected in the alpha index. The recommended upper limit concentration of ^{226}Ra is 200 Bq kg^{-1}, for which $I_\alpha = 1$. As can be observed from Table 1, the activity concentration values of ^{226}Ra in all the building materials are less than the recommended exemption level of 100 Bq kg^{-1} and $I_\alpha < 0.5$. Therefore, radon inhalation from the building materials under investigation is not so large as to restrict the use of these building materials in construction. Fig. 4 shows the variation of alpha index with building materials of Polur, Tamilnadu.

3.5.2. Gamma index (I_γ)

Another radiation hazard index, called the gamma activity concentration index, I_γ has been defined by the European Commission (1999) and Righi and Bruzzi (2006) is given,

$$I_\gamma = \frac{A_{Ra}}{300\ \text{Bq kg}^{-1}} + \frac{A_{Th}}{200\ \text{Bq kg}^{-1}} + \frac{A_k}{3000\ \text{Bq kg}^{-1}}. \quad (6)$$

The index I_γ is correlated with the annual dose rate due to the excess external gamma radiation caused by superficial material. Values of index $I_\gamma \le 2$ correspond to a dose rate criterion of 0.3 mSv year^{-1}, whereas $2 < I\gamma \le 6$ corresponds to a criterion of 1 mSv year^{-1} (European Commission, 1999; Anjos, 2005). Thus, the activity concentration index should be used only as a screening tool for identifying materials that might be of concern to be used as construction materials. But material with $I_\gamma > 6$ should be avoided, since these values corresponds to dose rates higher than 1 mSv year^{-1} (European Commission, 1999), which is the highest value of dose rate recommended for population (UNSCEAR, 2000). The European Commission (1999) suggests that building materials should be exempted from all restrictions concerning their radioactivity provided the excess gamma radiation originating from them does not increase the annual effective dose to a member of the public by more than 0.3 mSv year^{-1} (Righi and Bruzzi, 2006). Dose rates higher than 1 mSv year^{-1} should be permitted only in some very exceptional cases where materials are used locally. The index I_γ was estimated using Eq. (6). The distribution of values of the index I_γ for the building materials analyzed in this work is presented in Table 2. The gamma index I_γ in the present study ranges from 0.205 to 2.00, with mean of 0.43, which lies within the acceptable range up to 1.0 for material used in bulk amounts. All the values of $I\gamma$ are <2.0. Therefore, the annual effective dose delivered by buildings made of such materials is smaller than the annual effective dose constraint of 0.3 mSv. Hence, the building materials can be exempted from all the restrictions concerning radioactivity. Fig. 4 shows the variation of gamma index with building materials of Polur, Tamilnadu.

3.5.3. Internal hazard index (H_{in})

In order to limit the internal radiation dose from building materials to less than 1.5 mSv year^{-1}, a number of indoor exposure methods

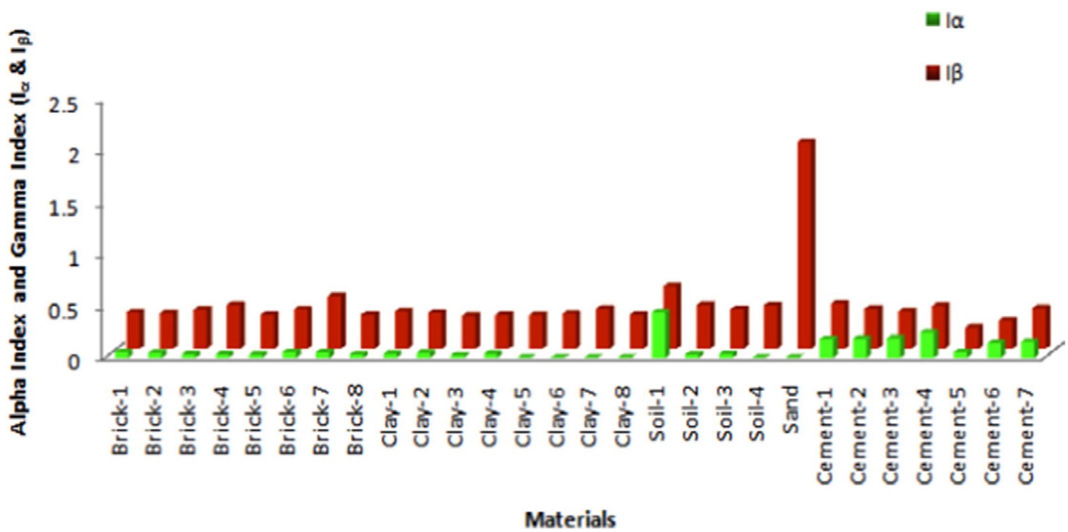

Fig. 4. Shows the variation of alpha index and gamma index in building materials of Polur, Tiruvannamalai District, Tamilnadu.

were suggested by some workers (Cottens, 1990; Quindos et al., 2000) and are given below

$$H_{in} = \frac{A_{Ra}}{185\ \text{Bq kg}^{-1}} + \frac{A_{Th}}{259\ \text{Bq kg}^{-1}} + \frac{A_k}{4810\ \text{Bq kg}^{-1}}. \quad (7)$$

The internal hazard index is defined so as to reduce the acceptable maximum concentration of ^{226}Ra to half the value appropriate to external exposures alone. For the safe use of materials in the construction of dwellings the following criterion was proposed by Krieger (1981), and is presented in Table 2.

$$H_{in} \leq 1 \quad (8)$$

The internal exposure to radon (Rn) and its decay product is controlled by internal hazard index. The mean value of H_{in} is determined to be 0.36 which is less than one which indicates that the internal hazards are less than the critical value. Fig. 5 shows the variation of internal radiation hazard index with building materials of Polur, Tamilnadu.

3.5.4. External hazard index (H_{ex})

The external hazard indices (H_{ex}) is given by a model proposed by Krieger (1981), and is presented in Table 2.

$$H_{ex} = \frac{A_{Ra}}{370\ \text{Bq kg}^{-1}} + \frac{A_{Th}}{259\ \text{Bq kg}^{-1}} + \frac{A_k}{4810\ \text{Bq kg}^{-1}} \leq 1. \quad (9)$$

In the present study, H_{ex} values vary from 0.153 to 1.552 with mean of 0.290, which is less than recommended limit. Fig. 5 shows the variation of external radiation hazard index with building materials.

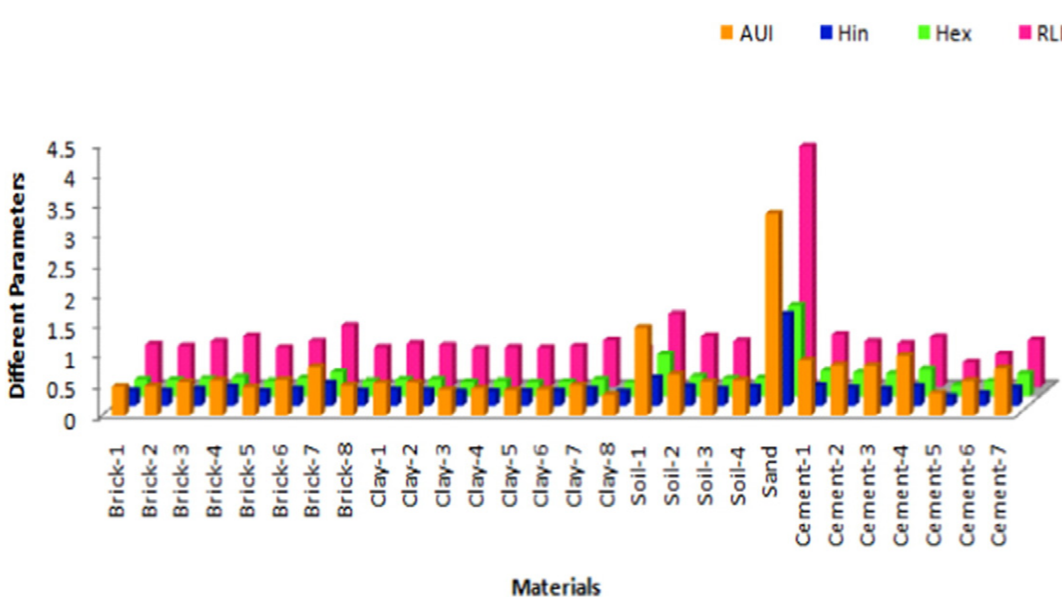

Fig. 5. Shows the variation of AUI, H_{in}, H_{ex} & RLI in building materials of Polur, Tiruvannamalai District, Tamilnadu.

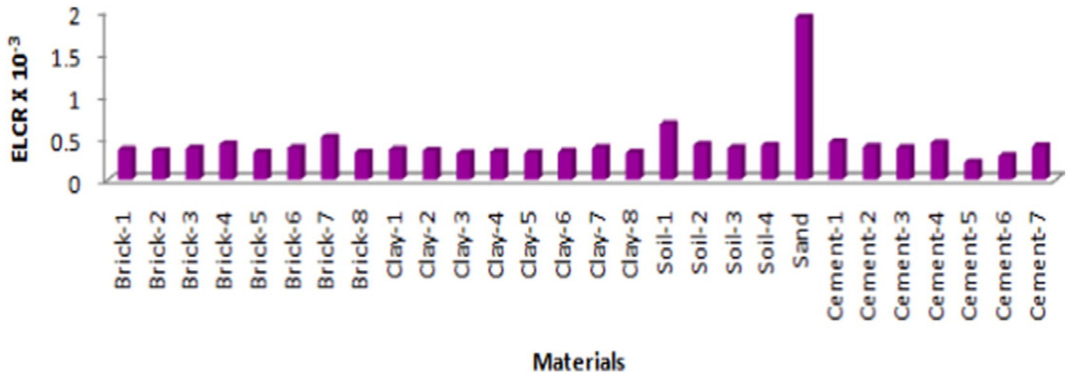

Fig. 6. Shows the variation of ELCR in building materials of Polur, Tiruvannamalai District, Tamilnadu.

3.6. Representative level index (RLI)

To estimate the level of gamma radioactivity associated with different concentrations of certain specific radionuclides, an index known as the representative level index is used (NEA-OECD, 1979; Sam and Abbas, 2001; Abbady, 2004; Alam et al., 1999b) and the formula is given as

$$RLI = \frac{1}{150\,A_{Ra}} + \frac{1}{100\,A_{Th}} + \frac{1}{1500\,A_K} \quad (10)$$

where A_{Ra}, A_{Th} and A_K are the average activity concentrations of ^{226}Ra ^{232}Th and ^{40}K, respectively, in units of Bq kg^{-1}. The calculated RLI values for the building materials are given in Table 2. The representative level index varies from 0.41 to 4.00 with an average of 0.86. It is clear that this average value does not exceed the upper limit for the RLI, which is unity (Alam et al., 1999a). Therefore, the above results show that these building materials present no radiation hazard and are not harmful to human beings. Fig. 5 shows the variation of representative level index (RLI) with building materials of Polur, Tamilnadu.

3.7. Activity utilization index (AUI)

Building materials act as sources of radiation and also as shields against outdoor radiation (UNSCEAR, 1993). In massive houses constructed of various building materials, such as stone, bricks, concrete or granite, the factor that most strongly affects the indoor absorbed dose is the activity concentrations of natural radionuclides in those materials, while the radiation emitted by outdoor sources is efficiently absorbed by the walls. Consequently, dose rates in indoor air will be elevated according to the concentrations of naturally occurring radionuclides in the construction materials that are used. To facilitate the calculation of dose rates in air from different combinations of the three radionuclides in building materials and by applying the appropriate conversion factors, an activity utilization index (AUI) can be constructed, as given by the following expression:

$$AUI = \frac{A_{Ra}}{50\ \mathrm{Bq\ kg^{-1}}} f_U + \frac{A_{Th}}{50\ \mathrm{Bq\ kg^{-1}}} f_{Th} + \frac{A_K}{500\mathrm{Bq\ kg^{-1}}} f_K \quad (11)$$

where A_{Ra}, A_{Th} and A_K are the actual values of the activities per unit mass (Bq kg^{-1}) of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in the considered building materials; f_{Ra}, f_{Th} and f_K are the fractional contributions to the total dose rate in air attributed to gamma radiation from the actual concentrations of these radionuclides. In the NEA-OECD (1979) report, the typical activities per unit mass of ^{226}Ra, ^{232}Th and ^{40}K in building materials A_{Ra}, A_{Th} and A_K are reported to be 50, 50 and 500 Bq kg^{-1}, respectively. The activity utilization index is weighted for the mass proportion of the building materials in a house by multiplying the characteristic activity associated with each material by a factor wm, which represents the fractional usage of those materials in the dwelling. To be more specific, full mass utilization (factor wm = 1) of a given material implies that all building materials used in a model masonry house are composed of this specific material. Half mass utilization (factor wm = 0.5) means that 50% of the masonry mass is composed of the material considered, and so on. For full mass utilization of a model masonry house (C_{Th} = C_{Ra} = 50 Bq kg^{-1} and C_K = 500 Bq kg^{-1}), the activity utilization index is unity by definition and is deemed to imply a dose rate of 80 nGy h^{-1} (UNSCEAR, 1993). The studied building materials can be evaluated in terms of whether they can be used for building construction by calculating the activity utilization index. The activity utilization index of the building materials was calculated using Eq. (10). The calculated values (Table 2) range from 0.34 (Clay-8) to 3.36 (Sand) with an average of 0.72. These values satisfy AUI<2, which corresponds to an annual effective dose rate 0.3 mSv $year^{-1}$ (El-Gamal et al., 2007). This indicates that these materials can be safely used for the construction of buildings. Fig. 5 shows the variation of activity utilization index with building materials of Polur, Tamilnadu.

3.8. Excess lifetime cancer risk (ELCR)

Another radiological parameter, the excess lifetime cancer risk (ELCR), was calculated using the following equation (Taskin et al., 2009) and is presented in Table 2

$$ELCR = AEDE \times D_L \times R_F \quad (12)$$

where *AEDE*, D_L and R_F are the annual effective dose equivalent, duration of life (70 years) and risk factor (0.05 Sv^{-1}), respectively. The risk factor is defined as the fatal cancer risk per sievert. For stochastic effects, the ICRP 60 uses a value of 0.05 for the public (Taskin et al., 2009). The calculated range of ELCR is 0.26×10^{-3} (Cement-5) 1.91×10^{-3} (Sand) with an average of 0.43×10^{-3} for five types of building materials. The average ELCR value is twice the world average (0.29×10^{-3}) (UNSCEAR, 2000). Fig. 6 shows variation of excess lifetime cancer risk (ELCR) with building materials of Polur, Tamilnadu.

3.9. Multivariate statistical analysis

Multivariate statistical analysis (MSA) involves observation and analysis of more than one statistical outcome variable at a time. In design and analysis, the technique is used to perform trade studies across multiple dimensions while taking into account the effects of all variables on the responses of interest (El-Arabi and Khalifa, 2002; Adam, 2012; Kulahci and Sen, 2008). In order to find out the interrelation among the radiological parameters calculated from natural radionuclides, the multivariate statistical analysis (Pearson's correlation analysis, Cluster analysis and Principal component analysis) has been carried out using SPSS for windows 16.0 software.

Table 3
Comparison of activity concentrations and radium equivalents (Bq kg^{-1}) in clay bricks in different areas of the world.

Country	$A_{(Ra)}$	$A_{(Th)}$	$A_{(K)}$	Ra_{eq}	Reference
Australia	41	89	681	220	Beretka and Mathew (1985)
China	41	52	717	171	Ziqiang et al. (1988)
Egypt	24	24.1	258	7	El-Tahawy and Higgy (1995)
Finland	78	62	962	241	NEA-OECD (1979)
Germany	59	67	673	207	NEA-OECD (1979)
Greece	49	24	670	135	Papastefanou et al. (1983)
Netherlands	39	41	560	141	Ackers et al. (1985)
Norway	104	62	1058	276	Stranden (1976)
Sweden	96	127	962	352	NEA-OECD (1979)
Sri Lanka	35	72	585	183	Hewamanna et al. (2001)
Kuwait	6.6	6.6	332	41.6	Bou-Rabee and Bem (1996)
Malaysia	233	229	685	612	Chong and Ahmad (1982)
Bangladesh	29	52	292	127	Chowdhury et al. (1998)
Pakistan	45	61	692	187	Tufail et al. (2007)
Present Work	5	23	374	61	–
World	35	30	400	–	UNSCEAR (2000)

In general, the required minimum sample size (number of observations-n) should be at least about 5 times the number of variables to perform the multivariate statistical analysis. In present work, the 5 radiological variables are selected for statistical analysis. Hence, the required number of observations $n > 5 \times 5 = 25$. In our case, the data fully satisfy this statistical condition.

3.9.1. Descriptive statistics

Tables 3, 4 and 5 gives the comparison of activity concentrations and radium equivalents (Bq kg^{-1}) in clay, cement and sand in different areas of the world, respectively. The descriptive statistics of minimum, maximum, mean, mode, median, standard deviation, variance, skewness, kurtosis were calculated for radionuclides and are given in Table 6. The standard deviation values of all the activity concentrations are higher than the mean value except for ^{40}K. In general, if the standard deviation is higher than the mean value then it indicates a low degree of uniformity and vice versa. Hence, a radioactive variable of the present study shows that low degree of uniformity. According to Adam and Eltayeb (2012), higher order variance implies a lower degree of homogeneity and higher degree of mobility. In the present study, all the radioactive variables show a higher order of variance. This shows a lower degree of homogeneity.

Skewness and kurtosis parameters are calculated for all the radionuclides (Table 6). Kurtosis values of all studied radionuclides are greater than zero which indicates that the distributions of these radionuclides in building materials are steeper than normal. The skewness values of

Table 4
Comparison of activity concentrations and radium equivalents (Bq kg^{-1}) in cement in different areas of the world.

Country	$A_{(Ra)}$	$A_{(Th)}$	$A_{(K)}$	Ra_{eq}	Reference
Australia	51.8	48.1	115	129	Beretka and Mathew (1985)
Australia	26.1	14.2	210	63.10	Sorantin and Steger (1984)
China	69.3	62	169	189	Ziqiang et al. (1988)
Brazil	61.7	58.5	564	189	Malanca et al. (1993)
Germany	26	18	241	70.30	NEA-OECD (1979)
United Kingdom	22.0	7.0	141	42.80	NEA-OECD (1979)
Sweden	55	47	241	141	NEA-OECD (1979)
Norway	30	18	241	74.30	NEA-OECD (1979)
Finland	44	26	241	99.70	NEA-OECD (1979)
Pakistan	31.3	26.8	212	85.90	Tufail et al. (2007)
Egypt	31.3	11.1	40.6	50.90	Sharaf et al. (1999)
Cuba	23	11	467	74	Brigido Flores et al. (2008)
Sicily	38	22	218	92	Rizzo et al. (2001)
Present work	37	34	188	102	–
World	35	30	400	–	UNSCEAR (2000)

Table 5
Comparison of activity concentrations and radium equivalents (Bq kg^{-1}) in sand in different areas of the world.

Country	$A_{(Ra)}$	$A_{(Th)}$	$A_{(K)}$	Ra_{eq}	Reference
Australia	3.7	40	44.4	65.30	Beretka and Mathew (1985)
China	39.4	47.2	573	151	Yu et al. (1992)
Brazil	14	18	807	102	Malanca et al. (1993)
Netherland	8.1	10.6	200	38.60	Ackers et al. (1985)
United States of America	37	33.3	18.5	86	Ingersoll (1983)
Hong Kong	24.3	27.1	841	128	Yu et al. (1992)
India	43.7	64.4	455.8	170.80	Viresh Kumar et al. (1999)
Pakistan	21.5	31.9	520	107	Tufail et al. (2007)
Egypt	9.2	3.3	47.3	16.60	Sharaf et al. (1999)
Cuba	17	16	208	55	Brigido Flores et al. (2008)
Present work	11	130	297	221	–
World	35	30	400	–	UNSCEAR (2000)

Table 6
Basic statistical summary of building materials of Polur, Tiruvannamalai District, Tamilnadu.

Variables	^{226}Ra	Log ^{226}Ra	^{232}Th	Log ^{232}Th	^{40}K
Mean	15.96	0.89	54.68	1.66	319.43
Median	7.96	0.90	42.81	1.63	343.51
Std. Deviation	19.4146	0.56	60.39	0.20	118.01
Variance	376.92	0.35	3648.00	0.04	13,930.00
Skewness	2.335	−0.23	5.05	3.19	0.17
Kurtosis	6.34	−0.59	26.29	14.37	0.75
Range	86.20	1.94	335.09	1.81	520.51
Minimum	BDL	BDL	23.47	1.37	113.43
Maximum	88.50	1.94	358.56	2.55	633.94
Frequency distribution	Log normal	Log normal	Log normal	Log normal	Normal

Statistical summary of Log ^{226}Ra and Log ^{232}Th calculated from logarithmic data.

^{226}Ra, ^{232}Th are greater than unity which shows these radionuclides positively skew towards lower concentrations (Ravisankar et al., 2014).

The distributions of radionuclides are studied by means of normal and log-normal. The normal represents the symmetrical distribution whereas log normal represents the asymmetrical distribution. As seen from Figs. 7-8, the concentration of ^{226}Ra and ^{232}Th shows the log normal distribution hence log ^{226}Ra, log ^{232}Th are calculated and given in Table 7 and Fig. 9 shows the distribution of ^{40}K is normal. Finally, log ^{226}Ra, log ^{232}Th, ^{40}K, log Ra(eq) and log AUI were used to perform the Pearson correlation, principal component and cluster analysis.

3.9.2. Pearson's correlation analysis

In order to determine the interrelation between the radionuclides (^{226}Ra, ^{232}Th and ^{40}K) and radiological variables in the building materials, Pearson correlation analysis was carried out. The Pearson's correlation coefficients among the radioactive variables are presented in Table 8.

A good positive correlation coefficient ($r = 0.605$) was observed between Log ^{232}Th and Log ^{226}Ra because radium and thorium decay series occur combined together in nature (Chandrasekaran et al., 2014; Ravisankar et al., 2014). But very weak negative correlation coefficient ($r = -0.617$) was observed between ^{40}K and Log ^{232}Th, Log ^{226}Ra since ^{40}K origins are in different decay series.

A positive correlation at $p < 0.01$ was found between the log Ra, log Th and log Ra_{eq} ($r = 0.329$; $r = 744$) due to concentration radium and thorium in building materials. Similarly, a significant positive correlation co-efficient was observed between log ^{226}Ra, log ^{232}Th and log AUI ($r = 0.329$; $r = 744$). This indicates that radium equivalent activity (Ra_{eq}) and activity utilization index (AUI) mainly depend on the concentration of radium and thorium in building materials. Hence, the total radioactivity in building materials of Polur is due to concentration of thorium and radium.

3.9.3. Factor analysis

Factor analysis (FA) is a statistical approach that can be utilized to analyze inter-relationships among a large number of variables and to describe these variables in terms of their common underlying dimensions (factors) (Ravisankar et al., 2015; Chandrasekaran et al., 2015). The statistical approach tries to find a way of condensing the information contained in a number of original variables into a smaller set of dimensions (factors) with a minimal loss of information (Kulahci and Sen, 2008). FA was carried out on the data set to assess the relationship by applying varimax rotation with Kaiser normalization. By extracting the eigenvalues and eigenvectors from the correlation matrix, the number of significant factors and the percent of variance explained by each of them were calculated. Table 9 shows the results of the factor loadings with a varimax rotation. The results indicate that there were two eigenvalues higher than one and that these two factors explain 62.76% of the total variance. The first factor explains 38.11% of the total variance and is mainly characterized by high positive loading of concentrations of log ^{232}Th, ^{40}K and radiological variable log Ra_{eq} (Table 9). Factor 2, was dominated by concentration of log ^{226}Ra and variable log AUI with 24.65% of variance. Hence, from factor analysis it can be concluded that gamma radiation emitted from concentration of thorium, potassium and radium in building materials.

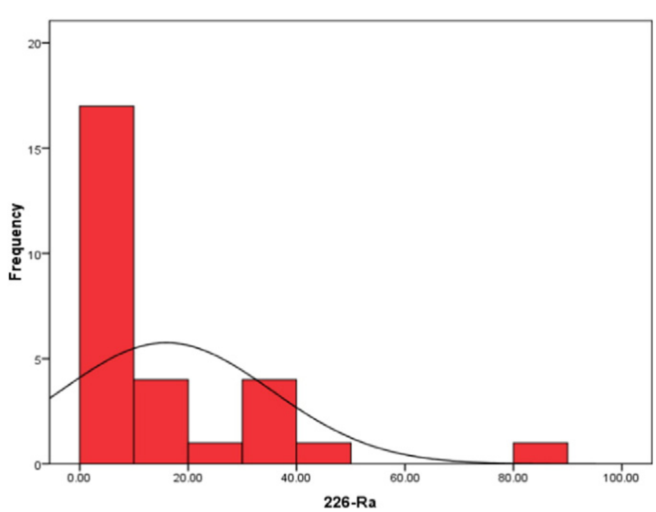

Fig. 7. Frequency distribution of ^{226}Ra in building materials of Polur, Tiruvannamalai District, Tamilnadu.

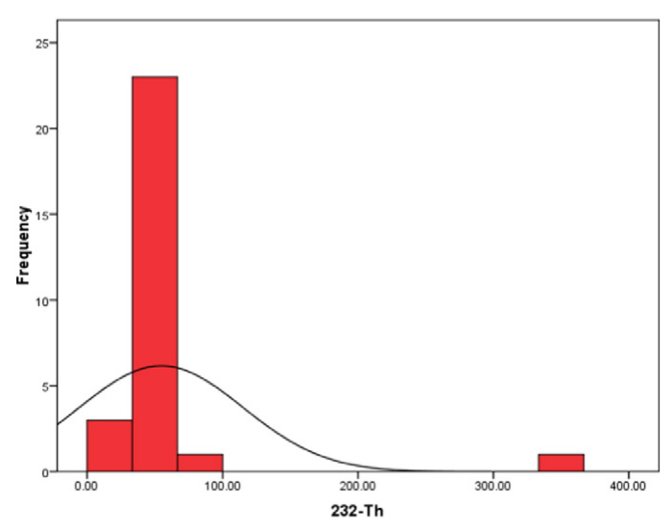

Fig. 8. Frequency distribution of ^{232}Th in building materials of Polur, Tiruvannamalai District, Tamilnadu.

Table 7
Log normal distribution of radioactive variables in building materials of Polur, Tiruvannamalai District, Tamilnadu.

Sample ID	Materials	Log ^{226}Ra	Log ^{232}Th	Log Ra_{eq}	Log AUI
PBI	Brick-1	1.04	1.53	1.97	−0.318
PB2	Brick-2	0.99	1.56	1.96	−0.313
PB3	Brick-3	0.83	1.68	2.01	−0.255
PB4	Brick-4	0.84	1.70	2.05	−0.233
PB5	Brick-5	0.81	1.59	1.94	−0.330
PB6	Brick-6	1.05	1.67	2.01	−0.228
PB7	Brick-7	1.03	1.84	2.14	−0.095
PB8	Brick-8	0.81	1.64	1.95	−0.301
PC1	Clay-1	0.89	1.65	1.99	−0.270
PC2	Clay-2	0.99	1.64	1.98	−0.264
PC3	Clay-3	0.68	1.57	1.93	−0.365
PC4	Clay-4	0.91	1.54	1.94	−0.349
PC5	Clay-5	BDL	1.63	1.94	−0.378
PC6	Clay-6	BDL	1.64	1.96	−0.363
PC7	Clay-7	BDL	1.71	2.02	−0.297
PC8	Clay-8	BDL	1.52	1.93	−0.465
PS01	Soil-1	1.95	1.60	2.23	0.165
PS02	Soil-2	0.82	1.80	2.07	−0.166
PS03	Soil-3	0.87	1.68	2.01	−0.249
PS04	Soil-4	BDL	1.78	2.05	−0.234
PSA1	Sand	BDL	2.55	2.75	0.527
CMT1	Cement-1	1.56	1.70	2.09	−0.038
CMT2	Cement-2	1.57	1.62	2.03	−0.076
CMT3	Cement-3	1.58	1.60	2.01	−0.081
CMT4	Cement-4	1.69	1.63	2.07	−0.002
CMT5	Cement-5	1.05	1.39	1.75	−0.428
CMT6	Cement-6	1.46	1.37	1.88	−0.239
CMT7	Cement-7	1.49	1.62	2.04	−0.107

3.9.4. Cluster analysis

Hierarchical cluster analysis is a statistical method for finding relatively homogeneous clusters of cases based on measured characteristics. It starts with each case in a separate cluster and then combines the clusters sequentially, reducing the number of clusters at each step until only one cluster is left (Kulahci and Sen, 2008). Hierarchical agglomerative cluster analysis was carried out on the normalized data by means of the complete linkage (furthest neighbor), average linkage (between and within groups) and Ward's methods, using Euclidean distances as a measure of relation (Kulahci and Sen, 2008). In the study, hierarchical clustering by applying average linkage method was performed on the standardized data set. The variables taken for this analysis are same as Pearson's correlation analysis. The cluster analysis result is shown in Fig. 10 and displays two clusters. Cluster-I consists of log ^{232}Th, log ^{226}Ra, log Ra_{eq} and log AUI. Similarly, Cluster-II consist only of ^{40}K. It is observed that concentration of radium, thorium and radiological variables such as radium equivalent activity (Ra_{eq}), activity utilization index (AUI) grouped in cluster-I show that variation of radium equivalent activity (Ra_{eq}), activity utilization index (AUI) depend on concentration of ^{232}Th and ^{226}Ra.

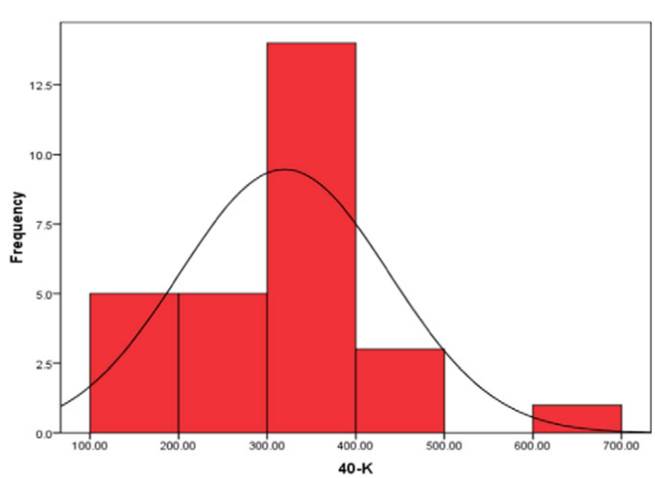

Fig. 9. Frequency distribution of ^{40}K in building materials of Polur, Tiruvannamalai District, Tamilnadu.

4. Conclusion

➢ The activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in various types of building materials commonly used in Polur of Tiruvannamalai Dist, Tamilnadu were measured using gamma ray spectrometry.

Table 8
Pearson correlation coefficients among the radiological variables of the building materials of Polur, Tiruvannamalai District, Tamilnadu.

Variables	Log ^{226}Ra	Log ^{232}Th	^{40}K	Log Ra_{eq}	Log AUI
Log ^{226}Ra	1				
Log ^{232}Th	0.605	1			
^{40}K	−0.617	0.547	1		
Log Ra_{eq}	0.329	0.921	0.488	1	
Log AUI	0.744	0.739	0.114	0.910	1

Table 9
Rotated factor loadings of radioactive variables of building materials of Polur, Tiruvannamalai District, Tamilnadu.

Variables	Factor 1	Factor 2	Communalities
Log ^{226}Ra	−0.499	0.855	0.980
Log ^{232}Th	0.565	0.033	0.320
^{40}K	0.980	−0.201	1.000
Log Ra_{eq}	0.567	0.339	0.436
Log AUI	0.237	0.587	0.400
% of Variance Explained	38.11	24.65	–
Cumulative variance explained (%)	38.11	62.76	–
Eigenvalue	1.91′	1.23	–
Total Communalities			3.136

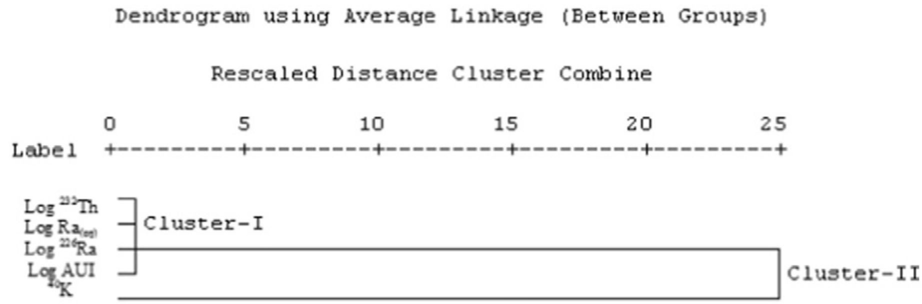

Fig 10. Shows dendrogram of clusters between radiological parameters.

- ➢ The radiation hazard parameters were evaluated and compared with international recommended values to assess the radiation hazard.
- ➢ The activity concentration and associated radiological hazards values were below the world permissible limit.
- ➢ Hence, the building materials investigated in this study can be recommended for safe usage for dwelling construction. The obtained data could be used as base line data for radiation assessment in building materials.
- ➢ Multivariate statistical analyses (cluster and factor) were carried out to recognize and classify the types of building materials to find out any relationship between the radioactivity and radiological variables in studied samples.
- ➢ Multivariate statistical analysis suggested that the emission of gamma radioactivity is mainly due to concentration of thorium and radium in building materials of Polur.

References

Abbady, A.G.E., 2004. Estimation of radiation hazard indices from sedimentary rocks in upper Egypt. Appl. Radiat. Isot. 60, 111–114.

Ackers, J.G., Den Boer, J.F., De Jong, P., Wolschrijin, R.A., 1985. Radiation and radon exhalation rates of building materials in The Netherlands. Sci. Total Environ. 45, 151–156.

Adam, A.M.A., Eltayeb, M.A.H., 2012. Multivariate statistical analysis of radioactive variables in two phosphate ores from Sudan. J. Environ. Radioact. 107, 23–43.

Ahmed, N.K., 2005. Measurement of natural radioactivity in building materials in qena city, upper Egypt. J. Environ. Radioact. 83, 91–99.

Alam, M.N., Chowdhury, M.I., Kamal, M., Ghose, S., Islam, M.N., Mustafa, M.N., Miah, M.M.H., Ansary, M.M., 1999b. The ^{226}Ra, ^{232}Th and ^{40}K activates in beach sand minerals and beach soils of Cox's bazaar, Bangladesh. J. Environ. Radioact. 46, 243–250.

Alam, M.N., Miah, M.M.H., Chowdhury, M.I., Kamal, M., Ghose, S., Islam, M.N., Mustafa, M.N., Miah, M.S.R., 1999a. Radiation dose estimation from the radioactivity analysis of lime and cement used in Bangladesh. J. Environ. Radioact. 42, 77–85.

Anjos, R.M., 2005. Natural radionuclide distribution in Brazilian commercial granites. Radiat. Meas. 39, 245–253.

Arafa, W., 2004. Specific activity and hazards of granite samples collected from the Eastern Desert of Egypt. J. Environ. Radioact. 75, 315–327.

Beretka, J., Mathew, P.J., 1985. Natural radioactivity of Australian building materials, industrial wastes and by-products. Health Phys. 48, 87–95.

Bou-Rabee, F., Bem, H., 1996. Natural radioactivity in building materials utilized in the state of Kuwait. J. Radioanal. Nucl. Chem. 213, 143–149.

Brigido Flores, O., Montalvan Estrada, R., Rosa Suarez, J., Tomas Zerquera, A., Hernandez Prez, A., 2008. Natural radionuclide content in building materials and gamma dose rate in dwellings in Cuba. J. Environ. Radioact. 99, 1834–1837.

Chandrasekaran, A., Ravisankar, R., Senthilkumar, G., Thillaivelavan, K., Dhinakaran, B., Vijayagopal, P., Bramha, S.N., Venkatraman, B., 2014. Spatial distribution and lifetime cancer risk due to gamma radioactivity in Yelagiri Hills, tamilnadu India. Egypt. J. Basic Appl. Sci. 1, 38–48.

Chandrasekaran, A., Ravisankar, R., Rajalakshmi, A., Eswaran, P., Vijayagopal, P., Venkatraman, B., 2015. Assessment of natural radioactivity and function of minerals in soils of Yelagiri hills, Tamilnadu, India by Gamma Ray spectroscopic and Fourier Transform Infrared (FTIR) techniques with statistical approach. Spectrochim. Acta A Mol. Biomol. Spectrosc. 136, 1734–1744.

Chong, C.S., Ahmad, G.U., 1982. Gamma activity of some building materials in West Malaysia. Health Phys. 43, 272–273.

Chowdhury, M.I., Alam, M.N., Ahmed, A.K.S., 1998. Concentration of radio nuclides in building and ceramic materials of Bangladesh and evaluation of radiation hazard. J. Radioanal. Nucl. Chem. 231, 117–122.

Cottens, E., 1990. Action against Radon at the International Level. Proceedings of the Symposium on SRBII, Journee Radon, Royal Society Of Engineers and Industrials of Belgium, Brussels (17 January).

EC (European Commission), 1999. Radiation Protection, 112- Radiological Protection Principles Concerning the Natural Radioactivity of Building Materials. Directorate - General Environment. Nuclear Safety and Civil Protection.

El-Arabi, A.-G., Khalifa, I.H., 2002. Application of multivariate statistical analyses in the interpretation of geochemical behaviour of uranium in phosphatic rocks in the Red Sea, Nile Valley and Western Desert, Egypt. J. Environ. Radioact. 61 (2), 169–190.

El-Gamal, A., Nasr, S., El-Taher, 2007. Study of the spatial distribution of natural radioactivity in upper Egypt, Nile River sediments. Radiat. Meas. 42, 457–465.

El-Tahawy, M.S., Higgy, R.H., 1995. Natural radioactivity in different types of bricks fabricated and used in cario region. Appl. Radiat. Isot. 46 (12), 1401–1406.

Faul, H., 1954. Nuclear Geology: a Symposium on Nuclear Phenomena in the Earth Sciences. Wiley.

Giuseppe, C., Garavaglia, M., Magnoni, S., 1996. Natural radioactivity and radon exhalation in stony materials. J. Environ. Radioact. 34 (2), 149–159.

Hewamanna, R., Sumithrarachchi, C.S., Mahawatte, P., Nanayakkara, H.L.C., Ratnayake, H.C., 2001. Natural radioactivity and gamma dose from Sri Lankan clay bricks used in building construction. Appl. Radiat. Isot. 54, 365–369.

Ingersoll, G.J., 1983. A survey of radionuclide contents and radon emanation rates in building materials in USA. Health Phys. 45, 363–368.

Kovler, K., Haquin, G., Manasherov, V., Ne'eman, E., Lavi, N., 2002. Natural radionuclides in building materials available in Israel. Build. Environ. 37, 531–537.

Krieger, R., 1981. Radioactivity of construction materials. Betonw. Fert. Tech. 47, 468–473.

Kulahci, F., Sen, Z., 2008. Multivariate statistical analyses of artificial radionuclides and heavy metals contaminations in deep mud of keban dam Lake, Turkey. Appl. Radiat. Isot. 66, 236–246.

Kumar, A., Kumar, M., Singh, B., Singh, S., 2003. Natural activities of ^{238}U, ^{232}Th and ^{40}K in some Indian building materials. Radiat. Meas. 36, 465–469.

Kumar, V., Ramachandran, T.V., Prasad, R., 1999. Natural radioactivity of Indian building materials and by-products. Appl. Radiat. Isot. 51, 93–96.

Malanca, A., Pessina, V., Dallar, G., 1993. Radionuclide content of building materials and gamma dose rates in dwellings of Rio Grade Do Norte, Brazil. Radiat. Prot. Dosim. 48, 199–203.

Mamont-Ciesla, K., Gwiazdowski, B., Biernacka, M., Zak, A., 1982. Radioactivity of building materials in Poland. In: Vohra, G., Pillai, K.C., Sadavisan, S. (Eds.), Natural Radiation Environment. Halsted Press, New York, p. 551.

Muhammad, I., Muhammad, T., Sikander, M.M., 2001. Measurement of natural radioactivity in marble found in Pakistan using a NaI(Tl) gamma-ray spectrometer. J. Environ. Radioact. 51, 255–265.

Nageswara Rao, M.V., Bhatti, S.S., Rama Seshu, P., Reddy, A.R., 1996. Natural radioactivity in soil and radiation levels of Rajasthan. Radiat. Prot. Dosim. 63, 207–216.

NEA-OECD, 1979. Exposure to Radiation from Natural Radioactivity in Building Materials. Report by NEA Group of Experts of the Nuclear Energy Agency. OECD, Paris, France.

Ngachin, M., Garavaglia, M., Giovani, C., Kwato Njock, M.G., Nourreddine, A., 2006. Assessment of natural radioactivity and associated radiation hazards in some Cameroonian building materials. Radiat. Meas. 42, 61–67.

Oktay Baykara, Sule Karatepe, Mahmut Dogru, 2011. Assessments of natural radioactivity and radiological hazards in construction materials used in Elazig, Turkey. Radiat. Meas. 46, 153–158.

Papastefanou, C., Manolopoulou, M., Charalambous, S., 1983. Exposure from the radioactivity in building material. Health Phys. 45, 349–361.

Quindos, L.S., Fernandez, P.L., Soto, J., 2000. Building materials as sources of exposure in houses. Radiation Protection Authorities in Denmark (RPAD), Finland, Iceland, Norway and Sweden Naturally Occurring Radiation in the Nordic Countries—Recommendations The Flag-Book Series (Reykjavik).

Radiation Protection Authorities in Denmark (RPAD), 2000. Finland, Iceland, Norway and Sweden Naturally Occurring Radiation in the Nordic Countries—Recommendations The Flag-Book Series (Reykjavik).

Ravisankar, R., Vanasundari, K., Chandrasekaran, A., Rajalakshmi, A., Suganya, M., Vijayagopal, P., Meenakshisundaram, V., 2012. Measurement of natural radioactivity in building materials of namakkal, tamilnadu, India using gamma ray spectrometry. Appl. Radiat. Isot. 70, 699–704.

Ravisankar, R., Vanasundari, K., Suganya, M., Raghu, Y., Rajalakshmi, A., Chandrasekaran, A., Sivakunar, S., Chandramohan, J., Vijayagopal, P., Venkatraman, B., 2014. Multivariate statistical analysis of radiological data of building materials used in tiruvannamalai, tamilnadu, India. Appl. Radiat. Isot. 85, 114–127.

Ravisankar, R., Sivakumar, S., Chandrasekaran, A., Kanagasabapathy, K.V., Prasad, M.V.R., Satapathy, K.K., 2015. Statistical assessment of heavy metal pollution in sediments

of east coast of Tamilnadu using Energy Dispersive X-ray Fluorescence Spectroscopy (EDXRF). Appl. Radiat. Isot. 102, 42–47.
Righi, S., Bruzzi, 2006. Natural radioactivity and radon exhalation in building materials used in Italian dwellings. J. Environ. Radioact. 88, 158–170.
Rizzo, S., Brai, M., Basile, S., Bellia, S., Hauser, S., 2001. Gamma activity and geochemical features of building materials: estimation of gamma dose rate and indoor radon levels in Sicily. Appl. Radiat. Isot. 55, 259–265.
Sam, A.K., Abbas, N., 2001. Assessment of radioactivity and the associated hazards in local and imported cement types used in Sudan. Radiat. Prot. Dosim. 93 (3), 275–277.
Sharaf, M., Mansy, M., El-Sayed, A., Abbas, E., 1999. Natural radioactivity and radon exhalation rates in building materials used in Egypt. Radiat. Meas. 31, 491–495.
Sorantin, H., Steger, F., 1984. Natural radioactivity of building materials in Austria. Radiat. Prot. Dosim. 7, 59–61.
Stoulos, S., Manolopoulou, M., Papastefanou, C., 2003. Assessment of natural radiation exposure and radon exhalation from building materials in Greece. J. Environ. Radioact. 69, 225–240.
Stranden, E., 1976. Some aspects on radioactivity of building materials. Phys. Nor. 8, 167–173.
Taskin, H., Karavus, M., Ay, P., Topuzoglu, A., Hindiroglu, S., Karahan, G., 2009. Radionuclide concentrations in soil and lifetime cancer risk due to gamma radioactivity in Kirklareli, Turkey. J. Environ. Radioact. 100, 49–53.
Tufail, M., Nasim-Akhtar, Sabiha-Javied, Tehsin-Hamid, 2007. Natural radioactivity hazards of building bricks fabricated from saline soil of two districts of Pakistan. J. Radiol. Prot. 27, 481–492.
United National Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000m. Sources and Risks of Ionizing Radiation. Report to the General Assembly with Annexes. United Nations, New York.
United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1988i. Sources, Effects and Risks of Ionizing Radiation. United Nations, New York.
United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1993i. Sources and Effects of Ionizing Radiation. Report to the General Assembly with Annexes. United Nations, New York.
Xinwei, L., Lingqing, W., Xiaodan, J., 2006. Radiometric analysis ofChinese commercial granites. J. Radioanal. Nucl. Chem. 267 (3), 669–673.
Yu, K.N., Guan, Z.J., Stokes, M.J., Young, E.C.M., 1992. The assessment of the natural radiation dose committed to the Hong Kong people. J. Environ. Radioact. 17, 31–48.
Ziqiang, P., Yin, Y., Mingqiang, G., 1988. Natural radiation and radioactivity in China. Radiat. Prot. Dosim. 24, 88–99.