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Technical Note

Effects of element composition in soil samples on the efficiencies of gamma energy peaks evaluated by the MCNP5 code

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ABSTRACT

In this work, self-absorption correction factor related to the variation of the composition and the density of soil samples were evaluated using the p-type HPGe detector. The validated MCNP5 simulation model of this detector was used to evaluate its Full Energy Peak Efficiency (FEPE) under the variation of the composition and the density of the analysed samples. The results indicates that FEPE calculation of low gamma ray is affected by the composition and the density of soil samples. The self-absorption correction factors for different gamma-ray energies which was fitted as a function of FEPEs via density and energy and fitting parameters as polynomial function for the logarithm neper of gamma ray energy help to calculate quickly the detection efficiency of detector. Factor Analysis for the influence of the element composition in analysed samples on the FEPE indicates the FEPE distribution changes from non-metal to metal groups when the gamma ray energy increases from 92 keV to 238 keV. At energies above 238 keV, the FEPE primarily depends only on the metal elements and is significantly affected by aluminium and silicon composition in soil samples.

1. Introduction

In studies of the low level activity of the environmental samples using gamma spectrometer with HPGe detector, voluminous samples are frequently used to increase the acquiring efficiency of the detector. However, count loss caused by self-absorption of gamma-ray in the sample material increases, especially for radionuclides emitting low energy photons (lower than 200 keV) [1]. The self-absorption coefficient for gamma-rays in the sample depends on many factors: sample density, composition, geometry of source-detector and gamma energy of the radionuclides in the analysed sample.

Many authors have developed different methods and techniques to determine the self-absorption coefficient in the sample. Self-absorption corrections can be both determined empirically and theoretically by using direct mathematical models or Monte Carlo method. By combination of the measurement of a ^{238}U reference sample with the MCNP5 simulation Huy et al. (2014) established the semi-empirical expression for calculating detecting efficiencies of HPGe detector in the gamma energies ranged from 185 to 1764 keV. Bolivar (1997), McMahon et al. (2004), Jodłowski et al. (2017) and Khater and Ebai (2007) discussed and justified the relationship between the sample density and gamma-ray energy [2–5]. Simple practical corrections for the photopeak are ineffective due to the discrepancies in the sample matrices [3,5]. Empirical functions which expressed the relationship between the full-energy peak efficiency (FEPE) with sample height, energy, matrix composition, and bulk density were illustrated [1,6]. Besides, difficulties of the efficiency calibration are due to the differences in sample size [1,2]. Długosz-Lisiecka and Bem (2013) conducted a study based on the comparison of two peak areas coming from other natural radionuclides [7]. The chemical composition has a major influence on the FEPE for low-energy gamma-rays of less than 150 keV [8–10]. The recent studies is a lot dealing with the applications of Monte Carlo Simulation code (MCNP5) in the nuclear field. For example, Bayoumi (2012) evaluated the isolation capacity of a new multi-barrier container made from cement and clay for radioactive waste by Monte Carlo method [11]. Damon (2005) studied the influences of Al and Pb composition in soil sample on the efficiency of detector using Monte Carlo method

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[12].

In this study, MCNP5 code (Monte Carlo Simulation code from Los Alamos Laboratory) was used to study the effects of sample composition and density which are considered as the main factors influencing on the gamma-ray self-absorption of the samples. Simulation models were then used to calculate FEPEs for composition and density of different samples. The correlation of the sample density and composition with the various gamma-ray energies were evaluated by using Factor Analysis (FA) method - a multivariate analytical technique. This method attempts to identify a few factors which are responsible for the correlation among a large of variables in terms of a few underlying, but directly unobservable, random quantities, called factors. There are three stages of factor analysis: a correlation matrix is generated, factors are extracted from the correlation matrix, the factors are rotated to maximize the relationship between factors and observation variables [13].

2. Materials and methods

2.1. Experimental setup for simulation

Activity concentration of natural radionuclides in the samples were determined by using a p-type coaxial HPGe of GC3520 from Canberra Industries Inc. which has a relative efficiency of 35% and an energy resolution of 1.8 keV FWHM at the 1332.5 keV peak of ^{60}Co. The Ge crystal has a diameter of 62.2 mm, height of 50.1 mm, its core hole has a diameter of 7.5 mm and depth of 23 mm, an aluminium window has a thickness of 1.5 mm. By the two line method using standard point source of ^{137}Cs, Loan et al. (2018) determined the outside dead layer thickness of this detector crystal to be 0.57 mm [14]. This value was used in simulation model of the detector for this study. Outside of lead shield chamber is covered with a 100 mm layer of lead and 10 mm of steel. However, X-rays in energies ranged from 75 keV to 85 keV are emitted due to the interactions between gamma-rays and shield lead. In order to minimize X-ray emitting from lead, layers of copper (Cu) and tin (Sn) with a thickness of 1.6 mm and 1 mm respectively are lined inside the lead chamber [15]. The system is operated by Lynx 32k MCA based on the digital signal processor (DSP). The Lynx is controlled by Genie 2000 program of Canberra Industries [16].

The influences of sample density and composition on the peak efficiency of the HPGe detector were studied for cylindrical source geometry. The sample geometry has its diameter d = 7.65 cm, its height h = 2 cm. Sample compositions of different soil types used in simulation were given in Table 1.

2.2. Methodology for the self-absorption correction determination

In practice, there are density and composition variations from sample to sample for a given sample geometry, and the offered calibration materials may have more slightly different chemical compositions than the investigated samples. It is the reason that we need to calibrate self-absorption between the analysed samples and reference samples. In this study, methodology for the self-absorption correction was developed using Monte Carlo simulation as follows:

For a given sample geometric setup, the factor of self-absorption correction **f** is expressed as the ratio of the peak efficiency for the investigated sample to the peak efficiency for the reference sample [1] and it is given by Eq. (1).

$$\varepsilon(E,\ h,\ \rho,\ c) = \varepsilon_0(E,\ h,\ \rho_r,\ c_r) \times f\ (E,\ h,\ \rho,\ c,\ \rho_r,\ c_r) \quad (1)$$

where $\varepsilon, \varepsilon_0$ are the efficiency for the investigated sample and reference sample respectively; h is the sample height; E is the gamma-ray energy (keV) of interest; ρ, c, ρ_r and c_r are density and sample composition for the investigated sample and the reference sample respectively.

Based on studies for the effects of the soil sample density to the peak efficiency, authors [2–4] proved that factor f depends on the sample density as Eq. (2):

$$f = a \times \exp(-b \times \rho) \quad (2)$$

where a and b are fitting parameters related to gamma-ray energy E, sample density ρ. In this work, we used the MCNP5 simulation code to evaluate this factor f.

2.3. Determination of the self-absorption correction factors by MCNP5 simulation

The MCNP5 code was utilized to simulate the particle transport process inside the detector, input data files were described based on the information of the geometry structure and reference materials from the manufacturer. The F8 tally and GEB card are used for simulating the pulse height distribution created by gamma photons transport in the germanium crystal of the detector [17]. It is noted that the program was performed on a core i5 Linux PC. The number of particle history was 1.5×10^9 for every simulated gamma energy to gain the statistical uncertainty of the peak efficiency of less than 0.1%.

Fig. 1 presented the experiment setup with HPGe detector simulated and illustrated by MCNP5 code. They include the cylindrical samples and HPGe detector placed in the lead shield chamber.

The Eckert & Ziegler's point sources consisting of ^{109}Cd, ^{133}Ba, ^{137}Cs, ^{54}Mn, ^{57}Co, ^{60}Co, ^{65}Zn were used for energy, FWHM, and efficiency calibration. These sources were located at 25 cm above the HPGe detector surface. The gamma-ray emitted from these sources were acquired by the HPGe detector. The FWHM data which was extracted from the obtained gamma spectra was fitted as a function of energies, according to Eq. (3):

Table 1
The chemical composition for six soil types used in simulation [16].

Materials	Chemical composition (%)													
	Si	Mg	Al	Fe	Mn	Ca	K	Tl	Na	H	O	N	S	C
Dirt1	26.2	–	8.5	5.6	–	–	–	–	–	2.2	57.5	–	–	–
Dirt2	31.6	–	7.2	3.1	–	–	–	–	–	1.1	55.8	–	–	1.2
Dirt3	–	–	–	–	–	–	–	–	–	10	78	0.4	0.2	11.4
Dirt4	25	2.5	8.3	12. 2	0.2	4.1	1.8	0.7	–	–	45.2	–	–	–
US. Avera	27.12	1.33	6.86	5.63	0.07	5.12	1.43	0.46	0.61	–	51.37	–	–	–
US. Wester	29.68	–	8.04	–	–	–	–	–	–	2.38	59.89	–	–	–

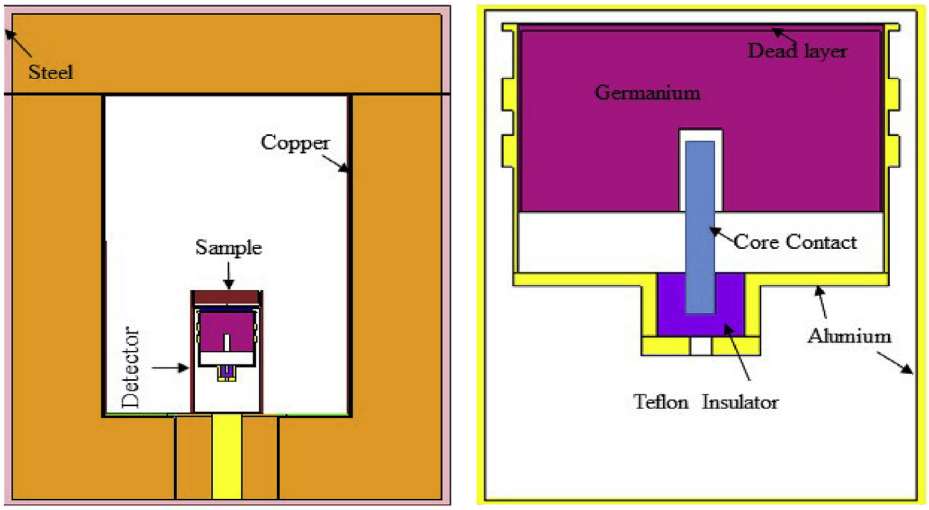

Fig. 1. Experiment setup with HPGe detector was simulated and illustrated by MCNP5 code.

$$FWHM = 0.000697 + 0.000744\sqrt{E + 0.427279\ E^2} \quad (3)$$

2.4. Factor analysis (FA)

Factor Analysis is a multivariate analytical technique. It is a statistical method used to describe for the correlation among a large of variables in terms of a few underlying, but directly unobservable, random quantities, called factors. It allows us to investigate concepts that are not easily measured directly by collapsing a large number of variables into a few interpretable underlying factors. There are several previous works related to using FA method for evaluating environmental data [11,18–22].

3. Results and discussion

3.1. True coincidence correction

When two or more gamma-rays emitted from the same radioisotope come to the detector at the same time, as a result, they are considered as only one gamma-ray because of the limited resolution time of the detector [1,23–25]. In this work, the radioactivity of ^{238}U, ^{232}Th determined via counting the multi-gamma emitted from their radioactive descendants, therefore, should be corrected for this effect. The ETNA program based on Peak to Total (P/T) method was used for this correction [26]. It required peak efficiency and total efficiency from the single-energy radioactive sources [23]. The peak efficiency and total efficiency used in the program from point sources and these sources were placed at 25 cm from the detector surface to avoid summing coincidence effects when spectra data acquisition was done. The Eckert & Ziegler's point sources consisting of ^{241}Am, ^{109}Cd, ^{137}Cs, ^{54}Mn, ^{65}Zn were used.

Present calculations show that true-coincidence effect does not require a correction at 63.3, 241.9, 295.2, 351.93 and 1764.49 keV gamma-ray emission for any of the studied geometries. Conversely, the true-coincidence effect is important for the main gamma rays of 609.31 keV, 1120.29 keV and 1238.10 keV, the values of the corrections is 1.173, 1.196 and 1.189, respectively for this case. In Table 2, these results were found nearly with the Huy et al. (2014) and Sahiner et al. (2014) [1,27]. This true-coincidence effect is one of the reasons accounting for the error of the calculated activity. It is therefore essential to calculated true-coincidence coefficient for the gamma ray lines from the ^{238}U and ^{232}Th series to obtain accurate absolute photopeak efficiencies for calculating activity.

3.2. Influence of sample density on FEPE

The evaluation of influence of sample density on FEPE was based on the methodology presented in section 2. The MCNP5 simulation model was used to calculate FEPE for soil sample $\varepsilon(E, h, \rho, c)$ and FEPE for reference sample $\varepsilon(E, h, \rho_r, c_r)$. The sample composition is Dirt 1 (see Table 1). Table 3 showed the simulated FEPE values $\varepsilon(E, h, \rho, c)$ via gamma energies for different densities of the soil sample. It is found from Table 3 and Fig. 2 that as the sample density increases, FEPE decreases near linearly as found in Khater and Ebaid (2007) study [5]. FEPEs for low-energy gamma-rays decrease faster than FEPEs for high-energy gamma-rays. For example, when the sample density is increased from 0.5 g cm^{-3} to 1.5 g cm^{-3}, the FEPE is reduced by 32% for the 46 keV gamma-ray energy, but only by 5% with 1764 keV gamma-ray energy. It is due to gamma rays enter the medium of higher material density cause more interactions with the atom of material and therefore more their energy loss before going to the detector to be recorded. Therefore, low-energy gamma rays have a less chance of passing through the sample material than high-energy gamma rays to be detected by detector. For the same sample geometry, this correction of density (by calculating f factor) is necessary to compensate for the variation of FEPE due to the change in sample density.

To do that, the FEPE for reference sample -$\varepsilon_0(E, h, \rho_r, c_r)$ needs

Table 2
True-coincidence effect in the present study in comparison with other studies.

E (keV)	Sahiner et al. (2014) [27]		Huy et al. (2014) [1]	This study
	$1/F_{TCS}$	F_{TCS}	F_{TCS}	F_{TCS}
63.30	0.992	1.008	–	1.001
241.9	–	–	1.002	1.006
295.20	1.000	1.000	1.000	0.998
351.93	0.999	1.000	1.000	1.002
609.31	**0.91–0.92**	**1.099**	**1.086**	**1.173**
1120.29	**0.908–0.910**	**1.100**	**1.111**	**1.196**
1238.10	**0.912–0.914**	**1.095**	**1.040**	**1.189**
1764.49	1.000	1.000	0.979	1.003
2204.21	–	–		0.996

Table 3
The simulated FEPE values ε(E, h, ρ, c) vs sample density for the different gamma energy.

E (keV)	ρ (g/cm^3)						
	0.5	0.75	1.0	1.25	1.5	1.75	2.0
46.5	0.0231	0.0208	0.0188	0.0171	0.0156	0.0143	0.0132
63.3	0.0571	0.0532	0.0497	0.0465	0.0436	0.0410	0.0386
92.7	0.0945	0.0898	0.0854	0.0813	0.0775	0.0739	0.0706
122.0	0.1016	0.0971	0.0930	0.0891	0.0854	0.0820	0.0787
238.6	0.0712	0.0688	0.0665	0.0644	0.0623	0.0604	0.0585
338.3	0.0529	0.0513	0.0498	0.0484	0.0471	0.0458	0.0445
351.9	0.0511	0.0496	0.0482	0.0469	0.0456	0.0443	0.0431
609.3	0.0322	0.0314	0.0307	0.0300	0.0294	0.0287	0.0281
1120.3	0.0199	0.0196	0.0192	0.0189	0.0186	0.0183	0.0180
1460.8	0.0160	0.0158	0.0156	0.0153	0.0151	0.0149	0.0147
1764.5	0.0136	0.0134	0.0132	0.0130	0.0129	0.0127	0.0125

to be determined. According to the method proposed by Huy et al. (2014) [1], the reference sample has no density and no composition, $\rho_r = 0$ and $c_r = 0$. Huy et al. (2014) proposed an extrapolation for the experimental curve of FEPE vs density under $\rho_r = 0$ [1]. As a results, there is still a presence of the sample composition c_r despite the zero density of sample by this extrapolation method. In this work, we improved this technique by using Monte Carlo simulation model to calculate FEPE for sample density of zero and sample composition of zero $\varepsilon_0(E, h, 0, 0)$. Besides, based on results of a presence of the sample composition c_r as the zero density of sample from Huy et al. (2014) [1], FEPE for sample density of zero and sample composition of nonzero $\varepsilon_0(E, h, 0, c_r)$ also were extrapolated from FEPE data simulated for the different composition of the soil samples (Dirt1, Dirt2, and Dirt3 [16] and density from 0.5 to 2 g/cm^3 similarly to data in Table 3.

The results were presented in Table 4. The ratios of two simulated FEPEs: $\varepsilon_0(E, h, 0, 0)/\varepsilon_0(E, h, 0, c_r)$ are larger than 1, especially at low energy proved there is a large discrepancy between FEPE for $\rho = 0$, $c = 0$and FEPE for $\rho = 0$, $c \neq 0$. For example, a discrepancy of 51% for 46.5 keV, 21% for 63.3 keV in sample Dirt2 and less than 3% for gamma-ray energy greater than 122 keV in Dirt3 sample. The cause of this discrepancy is due to the effects of chemical composition in the sample. Because when calculating FEPE for sample density of zero, the chemical elements in the sample have affected FEPE in the low energy gamma-ray. So, when this value of FEPE was extrapolated with sample density of zero, the effects of composition in the sample were not yet lost. It also showed the reason why the extrapolation method is only consistent for gamma-ray energy greater than 120 keV and not correct for low-energy gamma-ray. This is an advantage of Monte Carlo method.

From the simulated FEPE values of $\varepsilon_0(E, h, 0, 0)$ in Table 4 and the FEPE values for sample - $\varepsilon(E, h, \rho, c)$ in Dirt1 (see Table 3), the self - absorption coefficient $f(E, h, \rho, c, \rho_r, c_r)$ was calculated by equation (1) and presented in Fig. 2.

We can see in Fig. 2, the self - absorption correction factor decreases faster for low-energy gamma-rays than for high-energy gamma-rays. It depends strongly on the gamma ray energy and density of the sample. In order to parameterize the dependence of the self - absorption coefficient $f(E, h, \rho, c, \rho_r, c_r)$ on the sample density ρ (g/cm^3) for the different gamma-ray energies E(keV), the data in Fig. 3a were fitted using the Least-Squares Fit method based on equation (2). From that, the fitting parameters a and b were found as polynomial of logarithm neper of gamma ray energy:

$$a = 0.0147 \ln^3(E) - 0.2792 \ln^2(E) + 1.7525 \ln(E) - 2.6436, \quad R^2 = 0.9852, \tag{4}$$

$$b = -0.0086 \ln^4(E) + 0.2104 \ln^3(E) - 1.9224 \ln^2(E) + 7.7968 \ln(E) - 12.009, \quad R^2 = 0.9982. \tag{5}$$

3.3. Effects of material composition on FEPEyb

When analysing the soil sample with gamma-ray energy less than 150 keV, the material composition effect of the analysed sample should be taken into account [8,25]. It was also recognized from the comparison of the FEPEs of $\varepsilon_0(E, h, 0, c_r)$and $\varepsilon_0(E, h, 0, 0)$ of two methods in Table 4. In this section, the material composition effect on FEPEs was quantitively estimated. These FEPEs of the HPGe detector were calculated for six soil samples with different chemical composition in Table 1 using the MCNP5 simulation model. The soil sample was filled in a cylindrical container with its diameter of 7.65 cm, its height of 2 cm; and the sample density of 1.6 g/cm^3 was used.

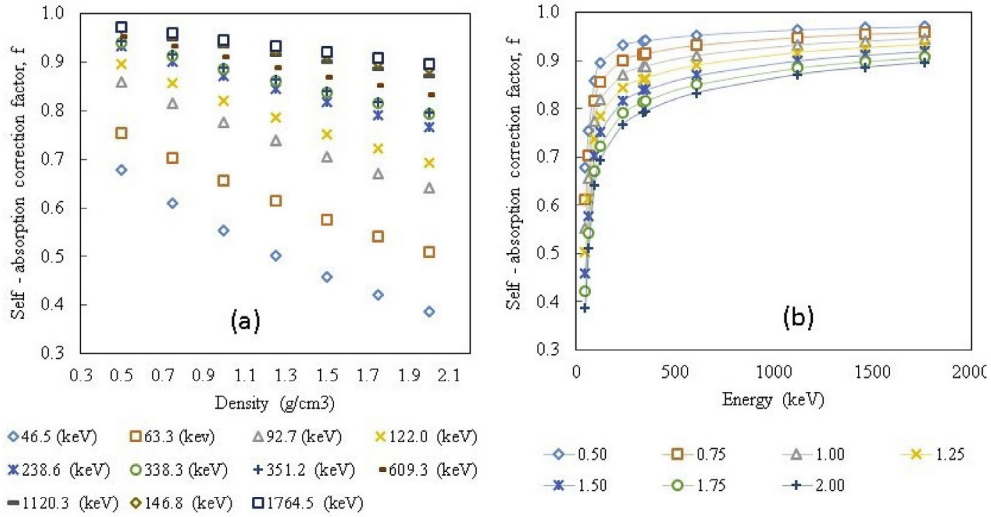

Fig. 2. The dependence of the self - absorption correction factor $f(E, h, \rho, c, \rho_r, c_r)$ on the sample density (g cm^{-3}) (Fig. 2a) and on the gamma-ray energy E(keV) (Fig. 2b).

Table 4
Comparison of the FEPEs from two methods.

Energy (keV)	$\varepsilon_0(E, h, 0, 0)$ (1)	$\varepsilon_0(E, h, 0, c_r)$			Ratio		
		Dirt1 (2)	Dirt2 (3)	Dirt3 (4)	(1)/(2)	(1)/(3)	(1)/(4)
46.54	0.0340	0.0249	0.0225	0.0285	1.37	1.51	1.19
63.30	0.0756	0.0647	0.0624	0.0653	1.17	1.21	1.16
92.70	0.1100	0.1038	0.1048	0.1044	1.06	1.05	1.05
122.00	0.1134	0.1104	0.1098	0.1103	1.03	1.03	1.03
238.63	0.0763	0.0759	0.0761	0.0758	1.01	1.00	1.01
351.93	0.0542	0.0540	0.0541	0.0542	1.00	1.00	1.00
609.31	0.0337	0.0336	0.0337	0.0337	1.00	1.00	1.00
1120.29	0.0206	0.0206	0.0206	0.0206	1.00	1.00	1.00
1460.82	0.0165	0.0165	0.0165	0.0165	1.00	1.00	1.00
1764.49	0.0140	0.0140	0.0140	0.0140	1.00	1.00	1.00

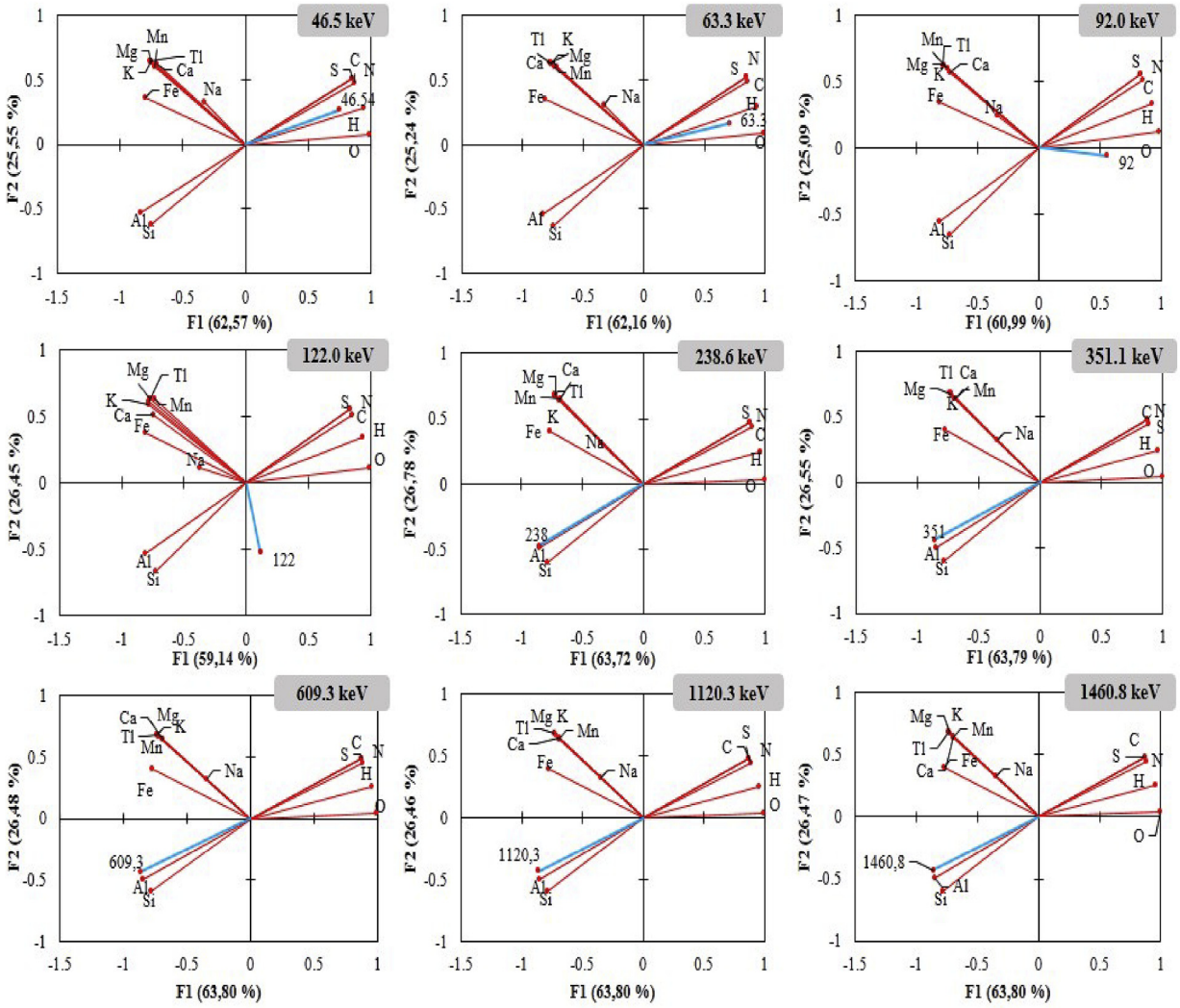

Fig. 3. Correlation between sample composition and FEPE of the investigated HPGe detector estimated by Factor Analysis method: red and blue lines are used to denote vector of material and efficiency, respectively in the plots. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The results of FEPE calculation for different energies of gamma-ray using MCNP5 simulation were shown in Table 5. It is seen from Table 5 that the detector FEPE is varied for the different material compositions. The most significant discrepancy of FEPEs was found between the Dirt3 and Dirt4 materials with the low-energy gamma-ray. Results revealed that the FEPE ratios with different material components at the low gamma-ray energies are varied from 6% to 70% for 46.54 keV, from 3% to 24% for 63.3 keV, and from 0.4% to 5% for 92 keV. In the meanwhile, all the relative differences of FEPE are less than 3% which can be ignored for the gamma-ray energies higher than 122 keV.

Greater differences for the FEPE can be seen in Dirt3 and Dirt4. The content of metal in Dirt4 sample is higher than 50% in contrast with the non-metal content in Dirt3 sample. The gamma

Table 5
Simulated FEPE values calculated for different material compositions.

Energy (keV)	MCNP Simulated FEPE					
	Dirt1	Dirt2	Dirt3	Dirt4	US. Avera	US. Wester
46.5	0.0151	0.016	0.0199	0.0117	0.0176	0.0138
63.3	0.0425	0.0438	0.0472	0.0379	0.0456	0.0411
92.7	0.076	0.0769	0.0774	0.0735	0.0777	0.0754
122.0	0.084	0.0845	0.0838	0.083	0.0848	0.0839
238.6	0.0615	0.0617	0.0606	0.0617	0.0616	0.0618

attenuation factors of Dirt4 samples are higher than other samples, especially in lower energies.

An alternative approach to evaluate the correlation between FEPEs and the sample compositions is the factor analysis (FA method). Following this method, based on the data of Table 5, the factor analysis firstly searches and generates two significant factors: F1 and F2. These two factors were selected as fundamental components in the coordinate (F1, F2). Then the data of observation vector in Table 5 were described in the coordinate F1 and F2 for different gamma-ray energies as in Fig. 3. It is noted from the figures that: The first factor correlates directly with the elements of $_{6}$C, $_{7}$N, $_{16}$S, $_{1}$H, $_{8}$O and indirectly with FEPE for specific gamma-ray energy. The second factor and the negative part of the first factor have a negative correlation with the elements of $_{12}$Mg, $_{11}$Na, $_{19}$K, $_{20}$Ca, $_{25}$Mn, $_{26}$Fe, $_{73}$Tl and $_{47}$Ag, $_{14}$Si.

It can be interpreted by the fact that the FEPEs for low-energy gamma-rays of 46.5 keV, 63.3 keV, and 92 keV correlate considerably with elements of $_{6}$C, $_{7}$N, $_{16}$S, $_{1}$H, and $_{8}$O; the FEPE vector for cross over gamma-ray energy of 122 keV has a tendency of moving to the elements with medium and heavy Z. When gamma-ray energy is higher than 238.6 keV, the FEPE vector does not vary and correlate with medium and heavy elements of $_{12}$Mg, $_{11}$Na, $_{19}$K, $_{20}$Ca, $_{25}$Mn, $_{26}$Fe, $_{73}$Tl and $_{47}$Ag, $_{14}$Si.

This has been clearly explained by the interaction mechanisms between gamma-rays and the material which were studied in many previous works. The higher the Z-number of material is, the greater the interaction of gamma radiation with it becomes, and the photoelectric absorption section of material will be large in the low-energy domain. Therefore, low-energy gamma-rays have a higher probability of escaping from the sample (avoiding self-absorption) and reaching the detector if sample contain many light elements. When samples contain heavier elements under higher concentration, the sample matrix contributes significantly to soft gamma-ray absorption and penetration of higher-energy gamma-ray, resulting in lower FEPE for low-energy gamma-ray groups [28]. Therefore, the self-absorption effect related to the variation of the composition and the density between the analysed samples and the calibration sample should be evaluated and corrected for bulk sample with low-energy gamma-ray in the sample analysis.

4. Conclusion

By the validated Monte Carlo simulation models, the influence of the composition and the density of soil samples on FEPE of HPGe gamma detector was evaluated from the comparison between the FEPE calculated by extrapolation of only zero density and the FEPE calculated by MCNP simulation for zero density and zero composition. A great difference between them at low gamma energies indicates the sample composition is also an important factor which needs to be corrected for detection efficiency of detector. The self-absorption correction factors which were evaluated and functionalized with the sample density for the different gamma-ray energies and their fitting parameters as polynomial of logarithm neper of gamma ray energy helps to calculate quickly the FEPE of detector. The FEPE ratios for different material components of surveyed soil samples are varied from 6% to 70% for 46.54 keV at the low gamma-ray energies and less than 3% which can be ignored for the gamma-ray energies higher than 122 keV. Finally, the influence of the soil composition on the FEPE was determined by six soil samples with different element compositions. The Factor Analysis gave an interesting estimation of the influence of sample composition on FEPE. It is considered only for the FEPE at the low energies (46.5 keV and 63.3 keV) and depends strongly on the non-metal elements in this energy range. On the other hand, the influence of the sample element composition on FEPEs changes from non-metal to metal groups in the energy domain from 92 keV to 238 keV. At energies above 238 keV, the FEPE is primarily influenced by the metal elements especially by aluminium and silicon in soil samples.

Declaration of competing interest

The authors whose names are listed immediately below report the following details of affiliation or involvement in an organization or entity with a financial or non-financial interest in the subject matter or materials discussed in this manuscript. Please specify the nature of the conflict on a separate sheet of paper if the space below is inadequate.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.06.013.

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