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Radiological Baseline Assessment of a Naturally Occurring Radioactive Material (NORM) Waste Disposal Facility in Ghana

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Abstract

Knowledge of accurate radio-isotopic signatures of NORM waste disposal site is essential prior to the disposal, to ascertain the baseline radioactivity levels. In this work, soil and water from a NORM waste site situated at Sofokrom in the Sekondi-Takoradi Metropolis of Ghana is characterized and determined. The mean activity concentration of 226Ra, 232Th, and 40K measured in the soil samples are 40.31 ± 13.93 Bq/kg, 63.29 ± 23.18 Bq/kg, and 198.71 ± 49.10 Bq/kg, respectively, with the 226Ra and 232Th average values being higher than the average worldwide values by UNSCEAR. Also, the average activity levels of water samples from monitoring borehole measured for 226Ra and 232Th are within the WHO guidance levels of 1 Bq/L. The radiological parameters such as internal and external hazard indices (Hin and Hex), absorbed dose rate (D), and radium equivalent activity (Raeq) are estimated to assess the radiological risk to human, and compared with other similar works. Except for the annual gonadal dose, the remaining parameters are less than the recommended values. Multivariate statistical analysis is done to establish the interrelations among the activity concentrations of the radionuclides and their radiological parameters using Pearson correlation coefficient and principal component analysis. Strong positive correlations between 226Ra, 232Th, and the radiological parameters are observed. These findings would serve as the reference point for assessing future variations in the background radioactivity level owing to the geological or human activities from the disposal of the oil waste in the environment, as well as to aid in improving the technical foundations for the management of the NORM waste.

Abbreviation List

GAEC	Ghana Atomic Energy Commission	**IAEA**	International Atomic Energy Agency
ICRP	International Commission for Radiation Protection	**NORM**	Naturally Occurring Radioactive Materials
HDPE	High Density Polyethylene	**LF**	Landfill
SF	Surroundings near Landfill	**UNSCEAR**	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization	**Max**	Maximum
CV	Coefficient of Variation	**Min**	Minimum
STD	Standard Deviation	**WVA**	Average Worldwide Values
PC	Principal Components	**PCA**	Principal Component Analysis
A	Activity Concentration	**AGD**	Annual Gonadal Dose
AED	Annual Effective Dose	**AUI**	Activity Utilization Index
DCF	Dose Conversion Factor	$\mathbf{E_{ing}}$	Committed Effective Dose for ingestion of water
DL	Duration of Life	**ELCR**	Excess Lifetime Cancer Risk
D	Absorbed Dose Rate	$\mathbf{I\gamma}$	Gamma Index
$\mathbf{H_{ex}}$	External Hazard Index	$\mathbf{H_{in}}$	Internal Hazard Index

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Ra_{eq}	Radium Equivalent Activity	**RF**	Risk Factor
RLI	Representative Level Index	**^{226}Ra**	Radium-226
^{232}Th	Thorium-232	**^{40}K**	Potassium-40
^{222}Rn	Radon-222	**Bq/L**	Becquerel per Liter
Bq/kg	Becquerel per kilogram	**L**	Liter
Surf	Surface	**cm**	centimeter
m	meter	**mSv**	millisievert (10^{-3} Sievert)
mSv/y	millisievert per year	**mL**	milliliter
$nGyh^{-1}$	nano Gray per hour	**µm**	micrometer
µSv/y	microsievert per year		

1. Introduction

Globally, Naturally Occurring Radioactive Materials (NORM) allied with the oil sector is an acknowledged problem and different disposal methods have been proposed by the international scientific community. Several petroleum production and exploration wastes, namely produced water, tank and pit bottoms, drill cuttings, waste oil, sludges and scales, pigging wastes (wastes removed from pipes), and soils contaminated with oil spills or produced water have considered the appropriate disposal method for these waste [1, 2]. The choice of disposal is mostly influenced by the physical form of waste, activity concentration, half-life, and the kind of radiation. The factors that must be considered in the selection of a suitable permanent or temporal disposal site include geology, climate, hydrology, hydrogeology, mineralogy, seismicity, and biota, among others [3].

Management of NORM waste, especially its disposal has recently been identified by the national regulatory bodies as a radiation safety and protection issue, and this requires the required attention. The appropriate disposal protocols that provide the right protection for both humans and the environment should be implemented. The methods for disposing of NORM wastes can be divided into four major categories: concentration and containment at approved waste disposal facilities; dilution and dispersion of the waste; disposal of the waste by reinjection; and treatment of the waste with another chemical [1, 4].

Surface disposal in the form of shallow land burial has been a long waste disposal method available to the oil sector. According to a research work by the American Petroleum Institute, shallow land burial is one of the possibilities for disposing of NORM waste [5], and is being done on a small scale in Texas [6] and three other territories in America [7, 8]. According to Hadley, there were significant remediation issues brought on by the disposal of sludge and scale in earthen pits [9]. The radiological evaluation of the disposal NORM waste in non-hazardous waste landfills as considered by Smith *et al.* [10] concluded that this method could be one of the oil sectors' most economical disposal choice.

Risk assessment is critical in determining the human and environmental effects including potential long-term consequences, resulting from groundwater contamination. There is also the need to carry out an occupational risk assessment to minimize exposures and reduce the contamination of public places [1]. This makes baseline studies extremely critical prior to NORM disposal to assess both the current radiological status and any potential upcoming contamination of the environment owing to the NORM disposal facility.

In Ghana, industrial activities leading to disposal of NORM have been carried out for several years with no knowledge of the radiological parts of these activities [2, 11]. The study therefore seeks to conduct a baseline study for a newly planned long-term disposal NORM waste disposal site at Zoil Services Limited in the west coast of Ghana based on the national and international best practices. In this work, activity concentrations of Ra, Th, and K in soil and water were determined using a gamma spectrometric technique. A comprehensive radiological risk assessment was carried out in the studied area using Radium Equivalent Activity (Raeq), Hazard indices (Hin and Hex), Absorbed dose rate (D), Annual Effective Dose Equivalent (AED), Annual gonadal dose (AGD), Representative Level Index (RLI), Activity Utilization Index (AUI), Gamma Index (Iγ), and Excess Lifetime Cancer Risk (ELCR). The distribution of the natural radionuclides was studied to understand the proper migration and further correlated the relation between the radionuclides and the radiological parameters by conducting Pearson correlation coefficient and principal component analysis (PCA). The acquired data will be important in determining the potential radiation exposure to the surrounding areas and serve as data for reference to any futuristic alterations in the radiation levels in the environment due to the NORM waste disposal facility in the environment.

2. Materials and Method

2.1. Description of studied area

The construction site, as presented in Figure 1, is situated in Sofokrom, Sekondi-Takoradi Metropolis, of the Westcoast of Ghana. The metropolis is the smallest district in the region but has the highest population, with a total land area of 192 km^2 [12, 13]. The site is situated about eighty (80) kilometers from the inhabited communities.

The topography of the whole area is varied, with ridges and hills dispersed throughout the area of undulating land. Capes and bays are very common along the coastline, and the central part of the metropolis is about 6 meters above the sea level. The geology of the area is characterized by fragmented sandstone and shale lying on a firm granite, gneiss, and schist basement. The surface area is well-watered, with a drainage system that resembles a trellis and a few tiny dendritic formations. This makes the site not prone to flooding and landslides [13, 14].

The design for the landfill is based on work performed by Smith *et al.* [10] in the USA with reference to the Argonne National Laboratory. Figure 2 illustrates the conceptual design of the planned disposal facility. The site is excavated to a depth of about 6.5 meters. A clay underlayment with thickness of approximately 1.2 meters is placed at the bottom and sides of the landfill to avert or reduce penetration of rainfall as well as discharge of leachate into the environment. A geomembrane linen and a layer of concrete will again serve as a barrier against seepage or leakage in case of spillage and additionally, serve as a cavity to ensure that the waste is kept in place. The NORM waste is wrapped and tightly sealed in High Density Polyethylene (HDPE) bags, and placed in concrete slaps and securely covered.

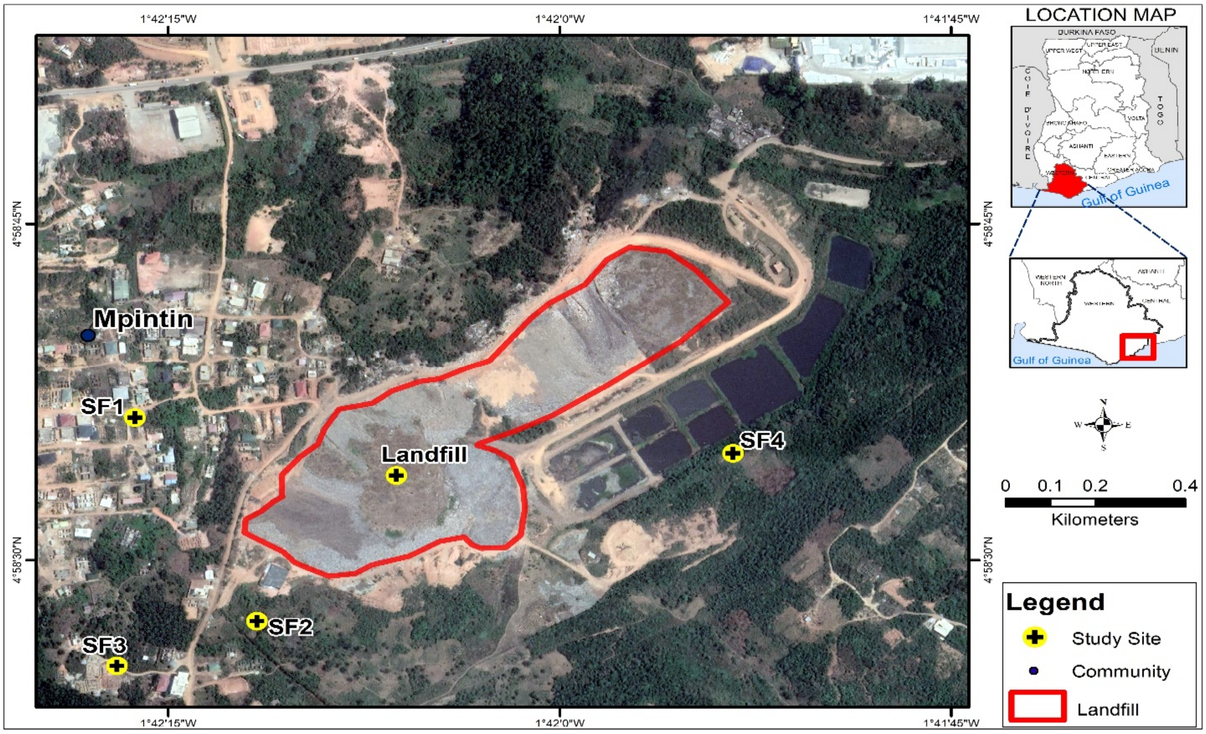

Figure 1. Satellite view of disposal site and sampling points.

2.2. Sample collection and preparation of samples

A total of thirty-six (36) samples comprising thirty-two (32) soil and four (4) water samples were taken at several positions within the disposal facility and surrounding areas. The soil samples were taken from varying depths of 5 cm (surface), 1 m, 2 m, 3 m from the site. The samples were sent to the Ghana Atomic Energy Commission (GAEC) for more analysis. The soil samples were air- and oven-dried, homogenized and sieved into a previously weighed 225 mL containers with 500 µm pore size mesh. They were sealed, weighed, and kept at ambient temperature for one month to enable ^{222}Rn and its short-lived progenies to achieve secular equilibrium with ^{226}Ra. Similarly, water samples taken from monitoring boreholes were also homogenized, and with no further preparation, put into a 1 L Marinelli beaker.

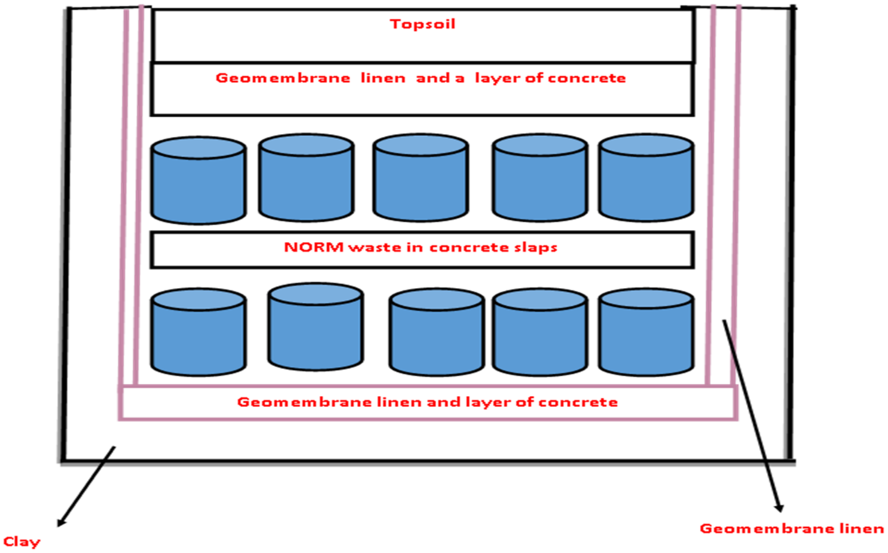

Figure 2. Conceptual design of NORM waste disposal facility.

2.3. Measurements of activity concentration

The samples were analyzed using a high-resolution gamma spectrometry with a p-type Extended Range Germanium coaxial detector (XtRa) with a relative efficiency of 40% and an energy resolution of 2.0 keV for gamma-ray energy of 1332 keV of ^{60}Co. The counting time for each sample was 36000 s. Each radionuclide was identified by the energies of their gamma-ray, and quantification of the radionuclides were done by the Genie 2000 gamma acquisition and analysis software. Using the spectra background, the gamma-rays peak area of the identified isotopes was corrected, and the spectra background was also used to evaluate the minimum detectable activity of ^{232}Th (0.33 Bq), ^{226}Ra (0.34 Bq), and ^{40}K (1.62 Bq) at 95% confidence. For the efficiency calibration of the gamma system, the IAEA reference materials IAEA-RGRa-1 (Ra-ore), IAEA-RGTh-1 (Th-ore), and IAEA-RGK-1 (K-ore) with densities (1.33 ± 0.03) were prepared into the identical containers as the soil samples with densities of (1.28 ± 0.10). The intensities and energies of the various radionuclides were all acquired from a recognized library [15].

The activity concentration, A (Bq/kg) for the radionuclide in the samples were evaluated using Equation (1) below:

$$A = \frac{N}{P(E) \times M \times n(E) \times T} \qquad (1)$$

where N (cps) = net peak area for the sample in the peak range, T (s) = counting time, P(E) = gamma emission probability, M (kg or L) = mass or volume of sample, and $Ƞ_{(E)}$ = efficiency of the photo peak obtained from the standard solution.

2.4. Radiological parameters

Radiological parameters determine the radiation effects on the exposure of human health and the environment [16]. These include Radium Equivalent Activity, Raeq (Equation (2)), Absorbed Dose Rate, D (Equation (3)), Annual Effective Dose, ADE (Equation (4)), committed effective dose, E_{ing} (Equation (5)), External Hazard Index, Hex (Equation (6)), Internal Hazard Index, Hin (Equation (7)), Annual Gonadal Dose, AGD (Equation (8)), Excess Lifetime Cancer Risk, ELCR (Equation (9)), Representative Level Index, RLI (Equation (10)), Activity Utilization Index, AUI (Equation (11)), Gamma Index, Iɣ (Equation (12)). The parameters were calculated using the equations as described in Table 1 to determine the radiological risk to the humans.

2.5. Multivariate statistical analysis

Multivariate analysis is usually conducted to obtain information that can be used in the interpretation of the environmental geochemical origin, while also achieving a great data compression efficiency from the primary data [31] . Additionally, large datasets can be streamlined and organized using this method to offer a significant insight. It can also be used to highlight unnoticed information by pointing out natural correlations between variables. In order to manage the environmental system, the relationships between variables were interpreted using this multivariate analysis to environmental data [32, 33]. This study used principal component analysis and Pearson's correlation analysis to determine the relation between the radiological parameters and the natural radionuclides. The statistical software used for the data analysis was an excel program called StatistiXL (version 2.0) and Minitab (version 21).

Table 1. Radiological Parameters with their equations and recommended values.

	Radiological parameter	Equation		Recommended value	Reference
1	Radium equivalent activity, Raeq (Bq/kg)	$Ra_{eq} = 1.43A_{Th} + A_{Ra} + 0.077A_{K}$	(2)	370	[17, 18]
2	Absorbed dose rate, D (nGyh^{-1})	$D = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_{K}$	(3)	84	[19, 20]
3	Annual effective dose, AED (mSv/y)	$AED = 8760\ (h/y) \times D\ (nGyh^{-1}) \times 0.2 \times 10^{-6} \times 0.7\ (Sv/Gy)$	(4)	0.48	[21, 22]
4	Committed effective dose, (ingestion for water samples) E_{ing} (mSv/y)	$E_{ing} = A_{w} \times I_{w} \sum_{j=1}^{3} DCF_{ing}\ (Th, Ra, K)$	(5)	0.1	[23, 24]
5	External hazard index, H_{ex}	$Hex = \frac{A_{Th}}{259} + \frac{A_{Ra}}{370} + \frac{A_{K}}{4810}$	(6)	1	[25, 26]
6	Internal hazard index, H_{in}	$Hin = \frac{A_{Th}}{259} + \frac{A_{Ra}}{185} + \frac{A_{K}}{4810}$	(7)	1	[25,26]
7	Annual gonadal dose, AGD (μSv/y)	$AGD = 4.18\ A_{Th} + 3.09\ A_{Ra} + 0.314\ A_{K}$	(8)	300	[22, 27]
8	Excess lifetime cancer risk, ELCR (mSv/y)	$ELCR = AED \times DL \times RF$	(9)	0.29	[21, 28]
9	Representative level index, RLI	$RLI = \frac{A_{Ra}}{150} + \frac{A_{Th}}{100} + \frac{A_{K}}{1500}$	(10)	1	[25, 29]
10	Activity utilization index, AUI	$AUI = \frac{A_{Ra}}{50} f_{Ra} + \frac{A_{Th}}{50} f_{Th} + \frac{A_{K}}{500} f_{K}$	(11)	2	[19, 21]
11	Gamma index, $I\gamma$	$I\gamma = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_{K}}{3000}$	(12)	1	[29,30]

$\mathbf{A_{Ra}}$, $\mathbf{A_{Th}}$, and $\mathbf{A_{K}}$ are the activities concentration of ^{226}Ra, ^{232}Th, and ^{40}K (Bq kg^{-1}), respectively, $\mathbf{A_{w}}$ is the activity concentration of the radionuclides in water in Bq/L; $\mathbf{I_{w}}$ is the intake of water (730 L/yr), $\mathbf{DCF_{Ing}}$ is the ingestion dose coefficient, i.e. $\mathbf{DCF_{Ra}}$ (2.8×10^{-7}Sv/Bq), $\mathbf{DCF_{Th}}$ (2.3×10^{-7} Sv/Bq), and $\mathbf{DCF_{K}}$ (6.2×10^{-7} Sv/Bq); **RF** and **DL** are risk factor (Sv^{-1}) and duration of life (70 years). For stochastic effects, ICRP 60 uses values of 0.05 for the public.

$\mathbf{f_{Th}}$ (0.604), $\mathbf{f_{Ra}}$ (0.462), and $\mathbf{f_{K}}$ (0.042) are the fractional contributions from the actual activities of ^{232}Th, ^{226}Ra, and ^{40}K to the total dose rate in air, respectively.

3. Results and Discussion

The activity concentrations of the primary radionuclides in soil from various depths of the NORM waste disposal facility and its surroundings is summarized in Table 2. For the various depth of the NORM waste disposal construction site, the activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K was between 21.34 to 86.58 Bq/kg, 25.90 to 117.58 Bq/kg, and 143.45 to 312.14 Bq/kg with a mean value of 40.31 Bq/kg, 63.29 Bq/kg, and 198.71, respectively (Table 2).

The mean values of ^{232}Th (63.29 Bq/kg) and ^{226}Ra (40.31 Bq/kg) are greater than the average worldwide values by UNSCEAR of 45 Bq/kg and 32 Bq/kg by a factor of 1.41 and 1.25, respectively. It was also noted that the radioactivity values were in the sequence of $^{226}Ra < {}^{232}Th < {}^{40}K$ in all the sampling sites with comparable studies stated by [34] and [35]. From the study, the radionuclides were not distributed equally through the various levels, and no distinct change was observed. Also the potential of these natural radionuclides to migrate varied greatly in the soil profile, which implied changes in the soil. The vertical distribution of radionuclides in the soil depth profile could differ, and was dependent on the conditions and individual processes of the soil [36].

Table 2. Activity concentration of the natural radionuclides (Bq/kg), radiological indices and the descriptive statistics of soil samples from the landfill (LF) and its surroundings (SF).

Sample ID	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	H_{ex}	H_{in}	AGD	D	AED	ELCR ×10^{-3}	RLI	AUI	I_γ
LF1 surf	32.58	98.16	188.19	187.45	0.51	0.59	570.05	82.19	0.10	0.32	1.20	1.20	1.32
LF1 1m	46.19	68.34	168.41	156.89	0.42	0.55	481.26	69.64	0.09	0.27	0.99	0.84	1.10
LF1 2m	35.90	48.21	153.37	116.65	0.32	0.41	360.62	52.10	0.06	0.20	0.72	0.60	0.82
LF1 3m	46.64	58.18	171.30	142.99	0.39	0.51	441.10	63.83	0.08	0.25	0.89	0.72	1.01
LF2 surf	45.70	83.26	186.22	179.10	0.48	0.61	547.71	79.17	0.10	0.30	1.14	1.02	1.26
LF2 1m	36.53	64.01	156.62	140.10	0.38	0.48	429.62	62.07	0.08	0.24	0.88	0.79	0.99
LF2 2m	33.14	52.77	160.07	120.89	0.33	0.42	373.26	53.86	0.07	0.21	0.75	0.65	0.86
LF2 3m	38.45	35.42	143.45	100.09	0.27	0.37	311.90	45.14	0.06	0.17	0.61	0.44	0.71
LF3 surf	22.42	50.75	177.47	108.64	0.29	0.35	337.15	48.41	0.06	0.19	0.66	0.63	0.78
LF3 1m	52.06	80.78	168.87	180.62	0.49	0.63	551.55	79.88	0.10	0.31	1.16	0.99	1.27
LF3 2m	37.01	74.87	150.23	155.64	0.42	0.52	474.50	68.59	0.08	0.26	1.00	0.92	1.10
LF3 3m	45.82	36.61	157.12	110.25	0.30	0.42	343.94	49.83	0.06	0.19	0.67	0.46	0.78
LF4 surf	45.00	66.92	173.90	154.09	0.42	0.54	473.40	68.46	0.08	0.26	0.97	0.83	1.09
LF4 1m	39.26	72.66	164.95	155.91	0.42	0.53	476.84	68.90	0.08	0.27	0.99	0.89	1.10
LF4 2m	38.42	48.45	154.70	119.60	0.32	0.43	369.82	53.47	0.07	0.21	0.74	0.60	0.84
LF4 3m	45.16	38.52	148.82	111.74	0.30	0.42	347.28	50.33	0.06	0.19	0.69	0.48	0.79
SF1 surf	23.77	46.45	205.16	106.02	0.29	0.35	332.03	47.59	0.06	0.18	0.62	0.58	0.76
SF1 1m	26.47	35.74	289.10	99.87	0.27	0.34	321.96	45.87	0.06	0.18	0.53	0.46	0.73
SF1 2m	31.84	59.40	206.88	132.67	0.36	0.44	411.64	59.21	0.07	0.23	0.81	0.74	0.94
SF1 3m	21.34	77.41	297.60	154.91	0.42	0.48	482.96	69.02	0.08	0.27	0.92	0.96	1.11
SF2 surf	30.49	37.59	233.42	102.23	0.28	0.36	324.63	46.52	0.06	0.18	0.58	0.48	0.73
SF2 1m	42.35	117.58	211.80	226.75	0.61	0.73	688.85	99.42	0.12	0.38	1.46	1.44	1.60
SF2 2m	24.67	38.54	195.97	94.90	0.26	0.32	298.86	42.85	0.05	0.17	0.55	0.48	0.68
SF2 3m	41.18	109.94	160.10	210.74	0.57	0.68	637.07	92.11	0.11	0.35	1.37	1.34	1.48
SF3 surf	27.63	25.90	191.34	79.37	0.21	0.29	253.72	36.39	0.04	0.14	0.44	0.33	0.57
SF3 1m	63.98	97.95	312.14	228.10	0.62	0.79	705.14	101.74	0.12	0.39	1.41	1.21	1.61
SF3 2m	33.90	92.97	186.47	181.21	0.49	0.58	551.92	79.59	0.10	0.31	1.16	1.14	1.28
SF3 3m	26.87	50.79	216.70	116.22	0.31	0.39	363.37	52.13	0.06	0.20	0.69	0.63	0.83
SF4 surf	62.54	63.18	281.73	174.58	0.47	0.64	545.81	78.80	0.10	0.30	1.05	0.79	1.24
SF4 1m	86.58	76.50	269.41	216.72	0.59	0.82	671.90	97.44	0.12	0.38	1.34	0.95	1.52
SF4 2m	59.07	66.72	197.44	169.68	0.46	0.62	523.41	75.82	0.09	0.29	1.06	0.83	1.19
SF4 3m	46.95	50.62	279.88	140.89	0.38	0.51	444.55	63.94	0.08	0.25	0.82	0.64	1.01
Mean	40.31	63.29	198.71	146.11	0.39	0.50	451.49	65.14	0.08	0.25	0.90	0.78	1.03
STD	13.93	23.18	49.10	40.76	0.11	0.14	121.85	17.69	0.02	0.07	0.28	0.28	0.28
CV	34.57	36.63	24.71	27.90	27.90	27.19	26.99	27.16	27.16	27.16	30.66	35.84	27.46
Min	21.34	25.90	143.45	79.37	0.21	0.29	253.72	36.39	0.04	0.14	0.44	0.33	0.57
Max	86.58	117.58	312.14	228.10	0.62	0.82	705.14	101.74	0.12	0.39	1.46	1.44	1.61
Skewness	1.30	0.59	1.07	0.47	0.47	0.58	0.50	0.49	0.49	0.49	0.39	0.58	0.48
Kurtosis	2.69	-0.26	-0.02	-0.66	-0.66	-0.29	-0.60	-0.61	-0.61	-0.61	-0.74	-0.27	-0.63
WVA	32.00	45.00	420.00	370	<1	<1	300	84	0.48	0.29	<1	2	≤ 1

The results of the Coefficient of Variation (CV) obtained were all below 40%, indicating a low degree of variation in sampling sites, Skewness is the absence of symmetry or asymmetry in the shape of the distribution frequency. Skewed distribution is a distribution that is non-symmetrical, and this could be positive or negative [37]. In this work, the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K radionuclides are positively skewed, and this indicates asymmetric distributions. The histograms in Figures 3, 4, and 5 show the distribution frequency of ^{226}Ra, ^{232}Th, and ^{40}K.

Kurtosis is a measure of heavily or lightly tailed relative to a normal distribution. It can therefore be a normal curve or mesokurtic (i.e. kurtosis is zero), more peaks compared to the normal curve or leptokurtic (i.e. kurtosis is positive), and less peaks compared the normal curve or platy kurtic (i.e. kurtosis is negative). The results obtained show that the kurtosis values of ^{226}Ra is positive indicating that is leptokurtic, while ^{232}Th and ^{40}K have negative kurtosis and is platy kurtic.

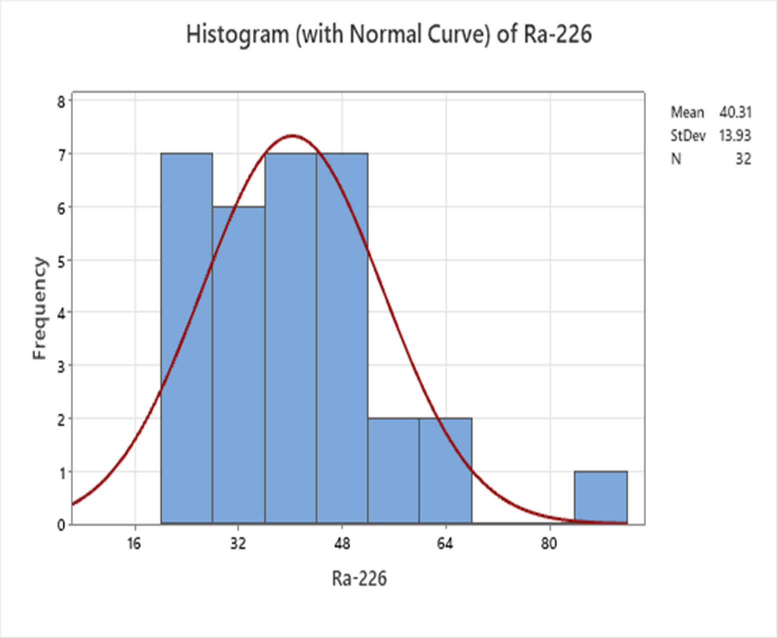

Figure 3. Distribution frequency of ^{226}Ra.

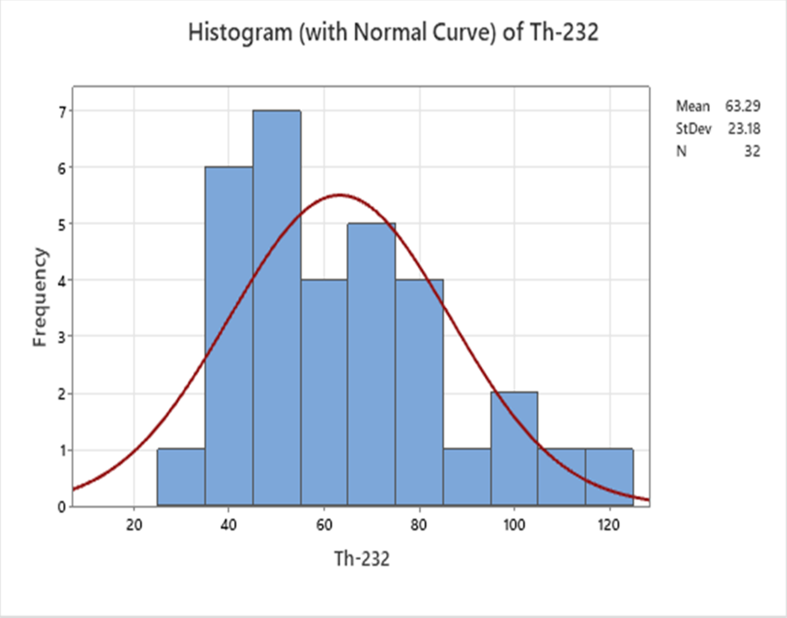

Figure 4. Distribution frequency of ^{232}Th.

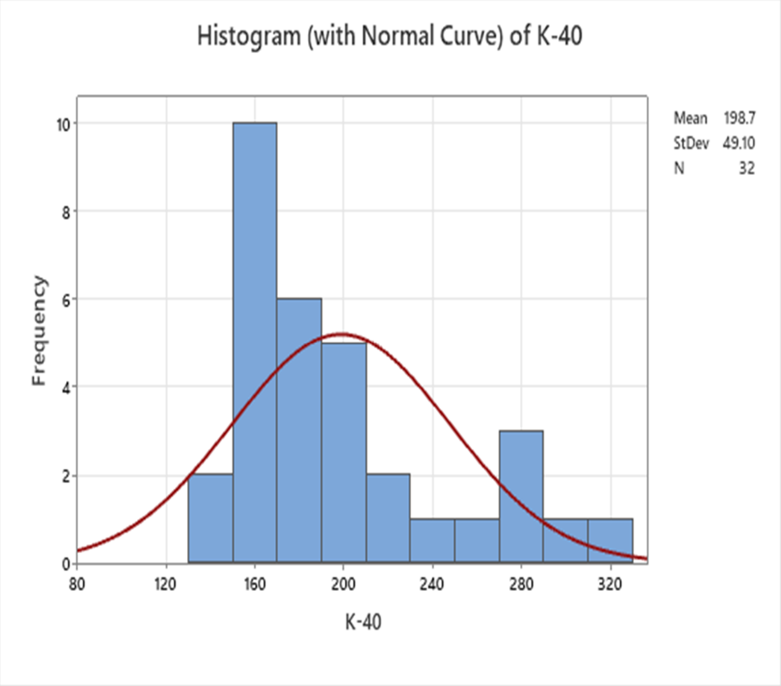

Figure 5. Distribution frequency of ^{40}K.

The activity concentration of radionuclides from the monitoring boreholes located around the NORM waste site is presented in Figure 6. The obtained results ranged from 04 to 0.8 Bq/L with an average of 0.6 ± 0.2 Bq/L for ^{226}Ra and ^{232}Th ranges from 0.1 to 0.5 Bq/L with an average of 0.33 ± 0.1 Bq/L. The results from this work were found to be with the guidance level (1 Bq/L) recommended by WHO [24].

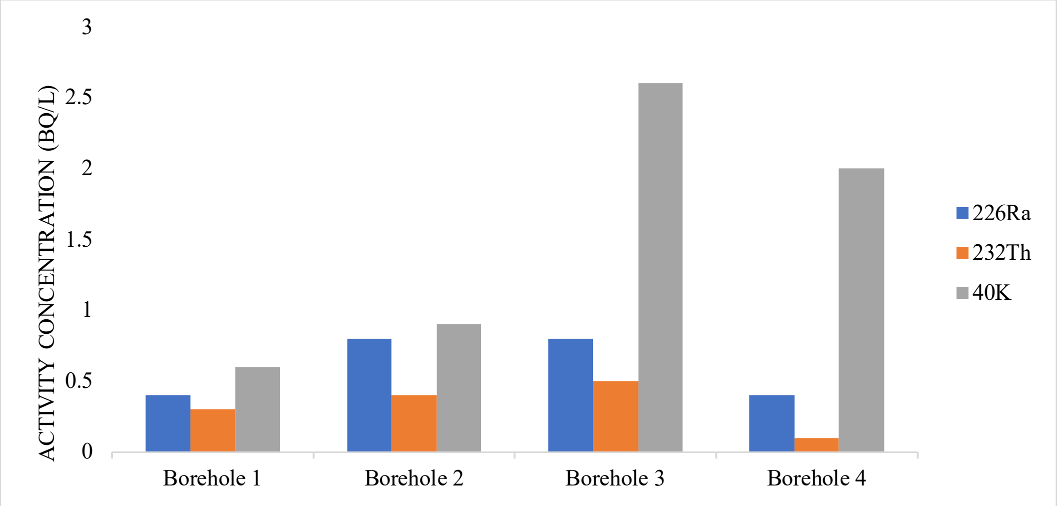

Figure 6. Activity concentration of radionuclides of monitoring boreholes around the NORM waste site.

3.1. Radiological indices

With the radiological indices, the average values of RLI and Iγ are slightly greater than recommended values (Table 3). The remaining radiological indices were within the recommended values expect annual gonadal dose, which is similar to the other reported works found in the literature. Senthilkumar's (India) and Chowdhury's (Bangladesh) work recorded high values of the absorbed dose rate than the world average values (Table 3). Therefore, the levels of radioactivity in the soil are of little radiological significance to the human health.

In assessing the risk from the contaminated soil, the effect of leakage of radionuclide into the soil when the waste is discharged into the landfill is determined using two risk scenarios. The first scenario is the risk of exposure to radiation for a who person resides on contaminated soil with radionuclide leak into the ground where a residential home has been constructed on the site. This assessment is usually based on the residential scenario taking into consideration the various exposure pathways including external exposure; radon and fugitive dusts inhalation; ingestion of soil, crops grown in the soil, and contaminated groundwater. The second scenario is the risk of exposure to radiation for an individual working on soil that has been contaminated with radionuclide leak into the ground. The risk of exposure to dose based on these two scenarios was carried out for worker (i.e. driver and technician) and the public i.e. someone living or farming close to the disposal facility.

Table 3. Evaluation of the radiological indices in the present study with other works across the globe.

Country	Raeq	Hex	Hin	AGDE	D	AEDE	ELCR × 10^{-3}	RLI	AUI	Iγ	Reference
Egypt	69.05	0.19	-	-	32.50	0.04	0.14	-	-	-	[26]
India	-	-	0.53	621.39	-	-	0.7	1.29	0.86	-	[27]
	99.35	0.27	0.33	316.72	45.19	0.06	0.19	0.72	0.71	-	[35]
	102.56	0.28	0.29	332.5	86.95	0.11	0.37	0.76	0.67	-	[37]
Ghana	61.00	0.16	0.20	-	27.55	0.19	0.73	-	-	-	[38]
Nigeria	16.82	0.05	0.05	-	8.00	0.01	-	-	-	0.13	[18]
	61.02		0.18	-	29.79	0.04	-	-	-	-	[39]
Bangladesh	151.00	0.41	-	-	71.3	0.09	-	-	1.07	-	[21]
	221.00	0.60	0.71	-	107	0.13	-	1.64	-	-	[40]
Turkey	138.00	0.38	-	-	68.65	0.08	-	-	-	-	[41]
Tunisia	38.60	0.10	0.13	-	18.5	0.02	-	-	-	-	[42]
Saudi Arabia	26.40	-	-	-	13.00	0.02	-	-	-	-	[43]
Russia	19.00	0.05	-	-	9.00	-	-	-	-	-	[44]
Ghana	146.11	0.39	0.50	451.49	65.14	0.08	0.25	0.90	0.78	1.03	This work
World values	370.00	<1	<1	300.00	84.00	0.48	0.29	<1	2	≤ 1	[45]

3.2. Pearson correlation matrix

Pearson correlation analysis was used to ascertain the relation amongst the radiological parameters and the natural radionuclides (Table 4). The outcomes generally show a strong positive correlation coefficient among the radiological parameters and ^{232}Th and ^{226}Ra. Hence, the relations show that the ^{226}Ra and ^{232}Th radionuclides primarily influence the gamma emission in the area. ^{40}K, on the other hand, has a weak correlation with the radiological parameters, and this implies that the concentration of ^{40}K is not much attributed to the radiological parameters.

Table 4. Pearson correlation matrix between the variables.

	Raeq	H_{ex}	H_{in}	AGDE	D	AEDE	ELCR	RLI	AUI	I_γ	^{226}Ra	^{232}Th	^{40}K
Ra_{eq}	1												
H_{ex}	1.000	1											
H_{in}	0.977	0.977	1										
AGDE	0.999	0.999	0.980	1									
D	0.999	0.999	0.982	1.000	1								
AEDE	0.999	0.999	0.982	1.000	1.000	1							
ELCR	0.999	0.999	0.982	1.000	1.000	1.000	1						
RLI	0.996	0.996	0.968	0.991	0.992	0.992	0.992	1					
AUI	0.939	0.939	0.846	0.929	0.927	0.927	0.927	0.950	1				
I_γ	1.000	1.000	0.974	1.000	0.999	0.999	0.999	0.994	0.940	1			
^{226}Ra	0.628	0.628	0.780	0.641	0.648	0.648	0.648	0.609	0.331	0.619	1		
^{232}Th	0.936	0.935	0.842	0.925	0.923	0.923	0.923	0.948	1.000	0.937	0.326	1	
^{40}K	0.264	0.264	0.274	0.298	0.290	0.290	0.290	0.173	0.131	0.284	0.225	0.116	1

3.3. Principal component analysis (PCA)

A 32 × 13 soil matrix of data was processed using correlation matrix due to the differences in the units as well as the variance of the radiological parameters and the concentrations of the natural radionuclide. The results of PCA show that two significant principal components (PCs) were determined based on eigenvalues greater than one [46] contributing to a total variance of 94.075% (Table 5). The first component accounted for 85.87% of the overall variance and a strong positive loading comprising mainly of D, Ra_{eq}, H_{in}, H_{ex}, I_{γ}, AEDE, ELCR, AGDE, RLI, AUI,^{226}Ra, and ^{232}Th. The second component contributed a total of 8.21% with a high positive loading of 0.803 by ^{40}K (Table 5). Therefore, it can be inferred that both ^{232}Th and ^{226}Ra dominantly enhance the radioactivity in the studied area.

Table 5. Loadings of principal component analysis.

Value	Explained variance (Eigenvalues)			Component loadings		
	Eigenvalue	Percentage of variance	Cumulative percentage	Variable	PC 1	PC 2
1	11.163	85.868	85.868	Raeq	0.998	-0.017
2	1.067	8.207	94.075	Hex	0.998	-0.017
3	0.770	5.925	100.00	Hin	0.980	0.114
4	0.000	0.000	100.00	AGDE	0.999	0.018
5	0.000	0.000	100.00	D	0.999	0.018
6	0.000	0.000	100.00	AEDE	0.999	0.018
7	0.000	0.000	100.00	ELCR	0.999	0.018
8	0.000	0.000	100.00	RLI	0.994	-0.102
9	0.000	0.000	100.00	AUI	0.932	-0.294
10	0.000	0.000	100.00	Iγ	0.995	-0.007
11	0.000	0.000	100.00	^{226}Ra	0.640	0.463
12	0.000	0.000	100.00	^{232}Th	0.929	-0.308
13	0.000	0.000	100.00	^{40}K	0.275	0.803

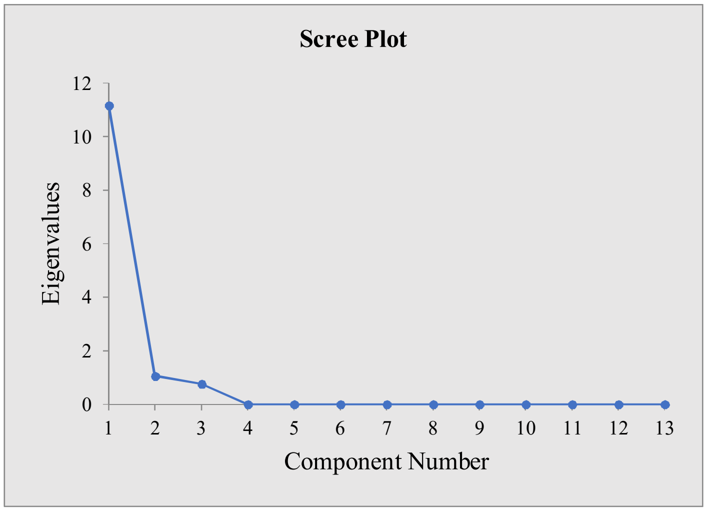

Figure 7. Scree plot of eigen values.

From the scree plot (Figure 7), the sudden decrease in the eigen value from component number 1 to component number 2 shows that the first component that makes up the larger portion of the variation accounts for most of the data variability. As a result, extracting two factors from all these appear to be acceptable [22]. The biplot of the two significant PCs is shown in Figure 8, indicating the pattern of distribution among the natural radionuclides and the radiological parameters with their site IDs. However, the ^{226}Ra and ^{40}K radionuclides are located opposite to ^{232}Th, thereby indicating an inverse relationship between these two groups of radionuclides. All the radiological parameters except for AUI formed a cluster thath is orthogonal to the ^{226}Ra and ^{40}K radionuclides, thus showing independence between most of the parameters and the two natural radionuclides. However, ^{232}Th influences the cluster of the radiological parameters due to its proximity (less than ninety degrees) to the radiological indices. Among the cluster of parameters, AUI is the most positively influenced index by the concentration of ^{232}Th. Furthermore, most of the landfill sites (LF) are affected by ^{232}Th radionuclide, whilst ^{226}Ra and ^{40}K are found within their surrounding (SF).

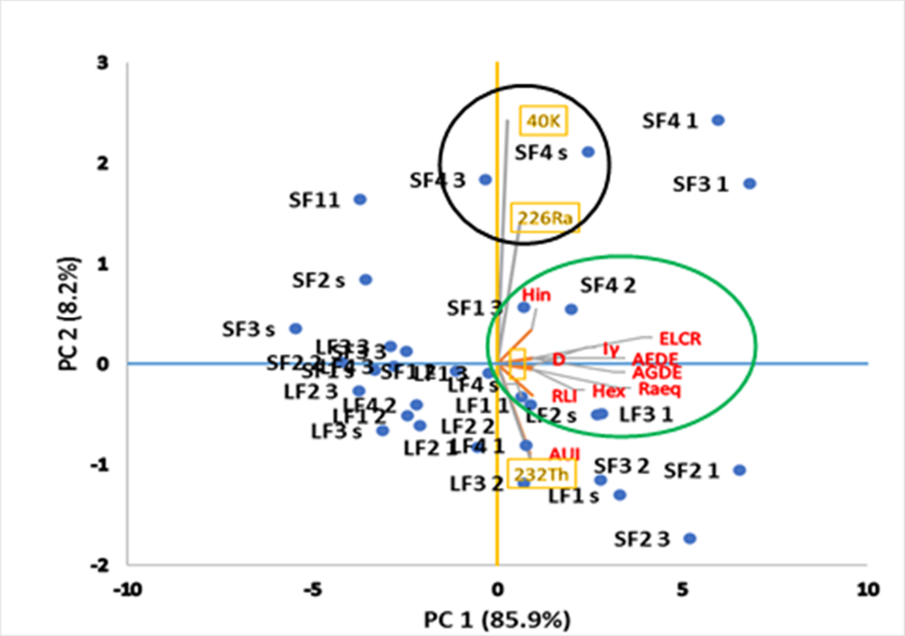

Figure 8. PCA of the natural radionuclides and the radiological parameters with their site IDs.

4. Conclusions

The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K of soil and water samples collected at the NORM waste disposal facility and environs in the Sekondi-Takoradi Metropolis of the Western Coast of Ghana were determined using gamma spectrometry. The present research work established that the radiological parameters obtained from this work were within the world recommended values, and therefore posed no immediate radiological risk to the workers and public. Correlations between the radiological parameters and natural radionuclides were calculated using pearson correlation coefficient. A strong positive correlation among the radionuclides (^{226}Ra and ^{232}Th) and the radiological parameters was observed as well as a weak correlation between ^{40}K and the radiological parameters. These findings of the Pearson correlation analysis are in line with those of the principal component analysis. This study will serve as the baseline for the upcoming research work to determine the likelihood of future radiological contamination owing to the activities of NORM waste disposal.

Conflicts of interest

The authors declare no conflicts of interest.

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ارزیابی پایه رادیولوژیکی تأسیسات دفع مواد رادیواکتیو طبیعی (NORM) در غنا

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چکیده:

آگاهی از علائم دقیق رادیویی ایزوتوپی محل دفع زباله NORM قبل از دفع، برای تعیین سطح پایه رادیواکتیویته ضروری است. در این کار، خاک و آب از یک سایت زباله NORM واقع در Sofokrom در کلانشهر Sekondi-Takoradi غنا مشخص و تعیین می‌شود. میانگین غلظت فعالیت ۲۲۶Ra، ۲۳۲Th و ۴۰K اندازه‌گیری شده در نمونه‌های خاک 31/40 Bq/kg ± 93/13، 29/63±18/23 Bq/kg و 198/10 ± 49/10 Bq/kg است که ۲۲۶Ra و ۲۳۲Th به‌ترتیب از میانگین مقادیر جهانی UNSCEAR بالاتر ا ست. همچنین، میانگین سطوح فعالیت نمونه‌های آب از گمانه مانیتورینگ اندازه‌گیری شده برای Ra226 و Th232 در سطوح راهنمایی ۱Bq/L، WHO است. پارامترهای رادیولوژیکی مانند شاخص‌های خطر داخلی و خارجی (Hin و Hex)، نرخ دوز جذبی (D) و فعالیت معادل رادیوم (Raeq) برای ارزیابی خطر رادیولوژیکی برای انسان تخمین زده شد و با سایر کارهای مشابه مقایسه می‌شوند. به جز دوز سالانه gonadal، پارامترهای باقی مانده کمتر از مقادیر توصیه شده است. تجزیه و تحلیل آماری چند متغیره برای ایجاد روابط متقابل بین غلظت فعالیت پرتوزا و پارامترهای رادیولوژیکی آنها با استفاده از ضریب همبستگی پیرسون و تجزیه و تحلیل مؤلفه‌های اصلی انجام شده است. همبستگی مثبت قوی بین ۲۲۶Ra، ۲۳۲Th و پارامترهای رادیولوژیکی مشاهده می‌شود. این یافته‌ها به عنوان نقطه مرجعی برای ارزیابی تغییرات آینده در سطح رادیواکتیویته پس‌زمینه به دلیل فعالیت‌های زمین‌شناسی یا انسانی ناشی از دفع زباله‌های نفتی در محیط، و همچنین کمک به بهبود پایه‌های فنی برای مدیریت ضایعات NORM است.

کلمات کلیدی: پارامترهای رادیولوژیکی، ضایعات نفتی، دفن سطحی، آنالیز چند متغیره.