



Assessment of the radioactivity of phosphogypsum at the General Phosphate Company in Anbar Governorate, Iraq

Mazen Katea Al-Gharrawy¹, Ibtihal Abduljaleel Al-Rubaye², Zaki Abduljabbar Alqaisi¹

¹Directorate of Nuclear and Radiation Safety and Security, Iraqi Atomic Energy Commission, Baghdad, Iraq
²Center for Treatment and Disposal of Chemical, Biological and War Waste, Scientific Research Commission, Ministry of Higher Education and Scientific Research, Baghdad, Iraq

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ABSTRACT

This study evaluates the potential radiological hazards associated with phosphogypsum waste; a byproduct generated by the General Company for Phosphates. Phosphogypsum waste is often considered an environmental hazard because it contains naturally occurring radioactive materials, primarily ²²⁶Ra. To assess the radioactivity levels in the phosphogypsum waste, 10 samples were collected from different locations. The samples were analyzed using high-purity germanium gamma spectrometry. The average activity concentration of ²²⁶Ra was 640.8 ± 12.3 Bq/kg. This level falls well within the international standard range established for ²²⁶Ra (15–1140 Bq/kg) and indicates that the radiological characteristics of the locally sourced material are comparable to those reported for other industrial sites worldwide. This study provides important baseline data on the radioactivity present in locally produced phosphogypsum waste, which may inform future environmental quality assessments and the development of safe waste management strategies.

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Corresponding Author:

Mazen Katea Al-Gharrawy

Directorate of Nuclear and Radiation Safety and Security,
Iraqi Atomic Energy Commission, Baghdad, Iraq

Email: mazenkatea5791@gmail.com



1. INTRODUCTION

Recently, there has been growing international recognition of the potential environmental and human health implications of Naturally Occurring Radioactive Materials (NORM), particularly when concentrated by large-scale industrial processes [1, 2]. The phosphate fertilizer industry is a major contributor to Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) because phosphate rocks typically contain elevated levels of uranium-238 and its decay products [3]. During the wet process production of phosphoric acid, these radionuclides are distributed between the finished product and the by-product, phosphogypsum (PG). As the largest waste stream generated by this process, phosphogypsum preferentially accumulates a significant portion of radium-226 [2, 4]. Globally, phosphogypsum is produced in large quantities and is commonly stored in open stacks near fertilizer production facilities. These stacks may represent a long-term source of radiological exposure through three primary pathways: external gamma radiation, radon exhalation, and the potential leaching of radionuclides into surrounding soil and groundwater systems [4, 5]. The most significant radioactive releases from this industry occur via liquid effluents, phosphate-laden dust, radon gas, and the solid phosphogypsum itself [6]. It has been estimated that approximately 100 Bq of U-238 per ton of treated phosphate is released into the environment as dust during drying and grinding processes. Reported activity concentrations of radionuclides in phosphogypsum vary considerably depending on the geological origin of the phosphate rock and the processing technology applied [3, 5]. Within the Arab region, previous studies have demonstrated this variability: in Egypt, phosphogypsum from the Suez Governorate showed radium-226 levels ranging between 250 and 600 Bq/kg [7], while in Jordan, levels reached approximately 580 Bq/kg, which is significantly higher than natural background levels [8].

This variability underscores that regional data cannot be generalized, and site-specific assessments are essential for accurate radiological characterization. In the Iraqi context, however, a significant knowledge gap exists. Despite the presence of major phosphate deposits in the Akashat region—one of the most important phosphate formations in Asia, as shown in Figure 1, located approximately 80 km northwest of Rutba—no published data are currently available on the radioactivity levels of phosphogypsum produced by the General Company for Phosphates. The absence of such baseline data precludes any meaningful assessment of the potential environmental and health risks posed by these materials to local soil, groundwater and hinders the development of national guidelines for their safe management or potential reuse.

Therefore, the present study aims to fill this gap by providing the first comprehensive radiological assessment of phosphogypsum generated at this facility. Using high-resolution gamma-ray spectrometry (HPGe), this research seeks to determine the activity concentrations of radionuclides, particularly ^{226}Ra in phosphogypsum samples; (ii) evaluate the associated radiation exposure risks; (iii) compare the findings with international reported values and regional studies from Egypt and Jordan; and (iv) establish a baseline dataset to support environmental monitoring and radiation protection strategies in the Iraqi phosphate industry. The distribution of radionuclides during phosphoric acid production follows consistent patterns globally: uranium isotopes concentrate in the phosphoric acid product, while radium-226 preferentially partitions into the phosphogypsum byproduct [2,4,14]. Recent comprehensive studies by Hill et al. [14] analyzing a global dataset of phosphate rocks, fertilizers, and phosphogypsum confirmed that ^{226}Ra retention in phosphogypsum ranges from 60-100% of the original activity in the parent phosphate rock. This partitioning pattern has been documented across diverse geological contexts, from Senegalese phosphogypsum showing ^{226}Ra activities requiring radiological monitoring [4] to Romanian stacks with hot spots reaching 5278 Bq/kg [9]. The variability in reported activity concentrations—ranging from 15 to 1140 Bq/kg globally—reflects differences in the geological origin of phosphate rocks and processing technologies employed [2,4,14]. Consequently, site-specific assessments remain essential for accurate radiological characterization.

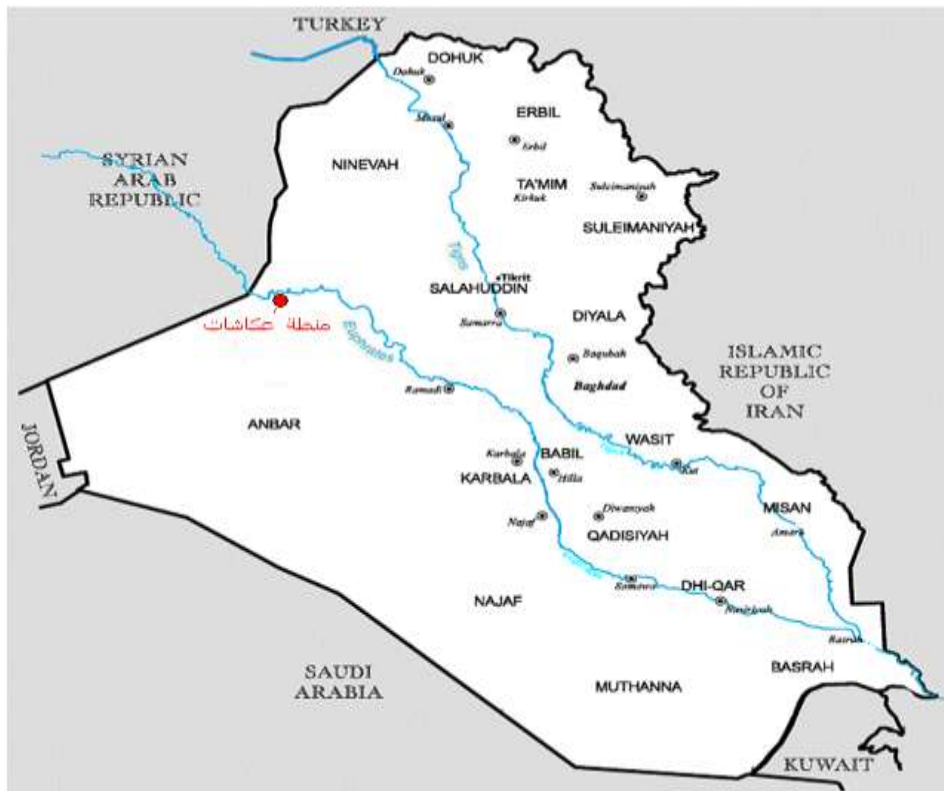


Figure 1. Map of Iraq showing the location of the General Phosphate Company/Akashat site.

2. The Comprehensive Theoretical Basis

2.1. Collection of Sample & Preparation Procedures (Sampling Preparation)

At the General Company for Phosphate facility located in Akashat, we collected ten representative samples that were representative of different storage locations. In each case, we collected approximately 2 kg of material from 0 cm to 20 cm at each location. To avoid contamination, we removed the surface layer of the material before sampling. All samples were sealed in polyethylene bags and sent to the laboratory for analysis. The samples in the lab were dried in the air using a room temperature procedure until they could no longer lose weight and then were dried in an oven at 105 degrees C for a period of 24 hours to remove any remaining moisture [9, 15].

After drying, the samples were crushed, homogenized, and passed through a 2 mm sieve to obtain uniform particle sizes. After the uniform-particle-size samples were generated, they were each placed into Marinelli beakers (or 250 mL cylindrical containers) with a cylindrical design. Hermetically sealed and stored for at least 30 days to achieve secular equilibrium between ²²⁶Ra and its decay products (²¹⁴Pb and ²¹⁴Bi) before gamma spectrometry measurement [1, 16]. This sealing period is critical, as it allows radon gas to reach equilibrium within the container, minimizing measurement uncertainties.

2.2. Calibration Process of the HPGe System

Energy calibration was performed using standard point sources (⁶⁰Co, ¹³⁷Cs, and ¹⁵²Eu) covering the energy range of 50-2000 keV. The calibration established a linear relationship between channel number and gamma-ray energy, with correlation coefficients exceeding 0.999 [10, 17]. Efficiency calibration was conducted using a certified mixed radionuclide standard source (containing ²⁴¹Am, ¹⁰⁹Cd, ¹³⁹Ce, ⁵⁷Co, ⁶⁰Co, ¹³⁷Cs, ¹¹³Sn, ⁸⁵Sr, and ⁸⁸Y) in the same geometry as the samples to minimize geometrical errors [2, 10, 17]. The full energy peak efficiency (ϵ) as a function of energy was fitted using a polynomial function:

$$\ln(\epsilon) = a_0 + a_1 \cdot \ln(E) + a_2 \cdot [\ln(E)]^2 + a_3 \cdot [\ln(E)]^3$$

E is the gamma-ray energy in keV

The efficiency calibration was verified by measuring a reference material with known activity (IAEA-RGU-1 or similar) and confirming that measured activities were within $\pm 5\%$ of certified values [10, 17]. Routine efficiency checks were performed every six months, with deviations maintained below 5% [10, 17].

2.3. Measurement Time and Counting Statistics (Measurement Procedure)

Each sample was measured for 60,000-86,400 seconds (approximately 16-24 hours) to achieve statistically significant counts and reduce counting uncertainty [1, 18]. The long counting time was necessary due to the relatively low activity concentrations and to ensure detectable peaks for all radionuclides of interest. The background spectrum was subtracted from each sample spectrum, with background measurements performed regularly using an empty container of identical geometry under the same conditions. Net count rates were converted to activity concentrations using the efficiency-calibrated photo peak areas.

2.4. Uncertainty Estimation and Quality Control

2.4.1. Combined standard uncertainties were calculated by propagating the following uncertainty components [2, 19]:

- Counting statistical uncertainty (1σ)
- Efficiency calibration uncertainty (typically 3-5%)
- Sample mass measurement uncertainty (<0.1%)
- Peak fitting uncertainty
- Background subtraction uncertainty
- The expanded uncertainty ($k=2$, corresponding to approximately a 95% confidence interval) is reported for all activity concentrations.

2.4.2. Quality control procedures included

- Regular background measurements to monitor detector contamination
- Daily energy calibration checks using reference peaks
- Participation in inter-laboratory comparisons where available
- Analysis of certified reference materials (e.g., IAEA-434 or IAEA-RGU-1) to validate measurement accuracy
- Duplicate sample analysis to assess reproducibility

For ²²⁶Ra determination, activity concentrations were calculated from the weighted mean of its decay products (²¹⁴Pb at 295.2 and 351.9 keV; ²¹⁴Bi at 609.3 keV) after confirming secular equilibrium [1, 16]. The potential for radon leakage from sample containers was minimized by using hermetically sealed containers and the 30-day ingrowth period, following the approach described by recent studies [1, 16].

3. METHOD

To ensure a representative sample of the site, samples were collected via radiometric survey from multiple locations (the phosphogypsum piles and the residential complex). To prevent contamination from the outside, non-metallic implements (such as wooden or plastic shovels) were utilized. Labeled with identifying tags (number, date, location, and depth), the samples were put in airtight plastic bags. After being brought to the lab, the samples were dried for 24 hours at 105–110°C in a convection oven until all moisture had been removed. Drying is done to prevent moisture from affecting the accuracy of radiometric readings. Following drying, the materials were crushed into fine, uniform grains using a specialized mill fitted with a ceramic or porcelain liner. To achieve a consistent grain size, the powder was ground and then sieved using a conventional sieve with apertures of 2 mm or less.

Each sample was weighed in a consistent quantity (often 100–500 grams, depending on the reagent's effectiveness and the size of the (measuring vessel), standard measurement containers (typically sealed round

plastic containers or Marinelli beakers) that had been previously dried and sanitized were used to hold each sample for measurement in a gamma-ray spectroscopy system (Figure 2) which consists of a pure germanium (semiconductor) detector with an efficiency of 40% and an energy separation power (2 keV - 1.33 MeV). The detector is cooled to 77 K (-196°C) when operating with liquid nitrogen, a high-efficiency protective barrier manufactured by the American company Canberra, the advanced Genie 2000 analytical software, Marinelli beakers for measuring radioactivity, and a digital spectrum analyzer, model DSA-2000A. [9]. The uranium decay chain measurements are impacted by radon-226 gas leaks, which were avoided by carefully sealing the containers. To allow for radiological equilibrium between radium-226 and its offspring (such as radon-222, lead-214, and bismuth-214), the samples were stored at room temperature for a minimum of 21 days. Following the equilibrium phase, the samples were moved to the gamma-ray spectroscopy apparatus, and the container was positioned in a fixed geometric configuration exactly above the high-purity germanium (HPGe) detector. Each sample underwent a 2- to 4-hour measuring process to provide a high-resolution radiological spectrum. To guarantee accuracy, each sample must be tested under the same experimental circumstances (temperature, container position, measurement length), and the detector must be spectrally calibrated using reference radioactive standards prior to each set of measurements.

Measurements of contamination levels and radiation exposure to the phosphogypsum collection areas were conducted using a portable device. RadEye readings of the radioactive contamination rate at the phosphogypsum collection sites, at a height of 3 cm from the ground surface, ranged from 1.6 to 1.8 cpm, while the device reading of the background radiation rate in the residential complex was 0.2 cpm, meaning that the radioactive contamination rate of the sites is 7 to 8 times the background radiation. The RadEye readings for radiation exposure at the phosphogypsum collection sites, at a height of 1 meter above the ground, ranged from 0.20 to 0.21 $\mu\text{Sv/h}$, while the RadEye PRD gamma ray detector with a scintillation detector (sodium iodide crystal) with an energy range of 60 KeV - 1.3 MeV, weighing 160 grams and with an internal memory to store 1600 measurements, used to measure the radiation background rate in the residential complex, was 0.02 $\mu\text{Sv/h}$. [10, 16]

4. RESULTS AND DISCUSSION

4.1. Results

The results showed: Surface radioactive contamination (3 cm): 7 to 8 times greater, ranging from 96 to 112 cps, as opposed to 12 cps in a residential neighborhood. Radiation exposure (1 m): 10 times greater. Ranging from 0.20 to 0.21 $\mu\text{Sv/h}$, then 0.02 $\mu\text{Sv/h}$ in a residential area. The samples' radioactivity of radium-226 was 640.8 ± 12.3 Bq/kg, falling within the globally documented range of 15 to 1140 Bq/kg. The results of laboratory analyses show that the radioactivity of radium (640.8 ± 12.3) and (522.8 ± 11.3) Becquerel/kg were obtained from (Table 3). This indicates the presence of uranium-238, which is evidence that the phosphogypsum contains uranium-238 isotopes. As shown in (Figure 4) of the graph. As shown in (Figure 4) of the graph, the concentrations of radionuclides in Bq/kg are in phosphogypsum samples. Laboratory measurements showed that the radioactivity of phosphogypsum in Iraq is within the average levels of radioactivity in other countries worldwide (Table 1). As a precaution, portable radioactivity surveys were conducted in the residential complex near the laboratory. The results indicated that the complex was not affected by the relatively high radioactivity background of phosphogypsum (Table 2) (portable device measurements of radiation rate, exposure, and location coordinates).

The non-appearance of the ^{40}K peak in the gamma ray spectra is due to its low concentration in the samples studied, in addition to the weak probability of emission at the energy of 1460 keV, and the high background radiation in the area under investigation, which made its intensity below the minimum sensitivity limit of the measurement system used. The findings show that phosphogypsum deposits contain comparatively significant levels of radioactivity. Concerns regarding environmental safety are raised by the observed exposure levels, which are much higher than the natural background, particularly if these regions are eventually used for residential or agricultural purposes. The requirement for efficient waste management plans and laws that specify the bounds for the safe use and recycling of phosphogypsum is further supported by the fact that the radioactivity value of radium is also within the upper limit of the worldwide range. The radiation dosage levels for the housing complex vary from 0.02 to 0.04 $\mu\text{Sv/h}$.

As can be seen from these readings (Figure 3), which fall below the typical range of background radiation levels in residential settings, they demonstrate relative stability and a steady decline in radiation levels. Regarding the heaps of phosphoric gypsum: The range of radiation dosage levels is 0.18 to 0.23 $\mu\text{Sv/h}$. The phosphoric gypsum material releases noticeably greater radiation levels, as seen by these measurements, which are three to 10 times higher than those in the housing complex. With values ranging from around 460 to 640, Ra-226 (red line, top in the picture) is the isotope with the greatest concentration across all samples. The largest concentrations (~640 and ~600) are seen on Pg2 and Pg7. Given that Ra-226 is one of the radioactive isotopes of the uranium family, this suggests a high amount of natural radioactivity. Bi-214 (orange line): Its concentration ranges from 370 to 500, following that of Ra-226.

Although its trend varies somewhat, it follows the same pattern as Ra-226, indicating that it is the product of Ra-226's decay (within the decay series). Because it is similarly a byproduct of the decay of Ra-

226, Pb-214 (dark orange line) has a pattern very similar to Bi-214. Its concentration, which ranges from 300 to 390, is marginally lower than that of Bi-214. In different samples, it shows relative stability. The isotope with the lowest concentration, Th-234 (pink line at the bottom), varies from 135 to 157. It doesn't fluctuate much and is really steady. Most samples show a close pattern of isotope concentrations, particularly between Bi-214, Pb-214, and Ra-226, which speaks to the radioactive equilibrium in the decay series. Pg2 and Pg7 present the highest amounts of the top three isotopes, which could be an indication of areas where more radioactive material exists. Th-234 remains virtually constant with no visible variation in any samples; thus, it can be inferred that there is a steady primary uranium supply. Concentrations are within the global average values [6].

Table 1. Shows the concentrations of radioactive isotopes in phosphogypsum for a group of countries (Bq/kg).

No	Country	Po – 210	Pb – 210	Ra - 226	U– 238
1	Spain	-	520	670	220
2	China	80	82	85	15
3	Indonesia	450	480	473	43
4	India	420	490	510	60
5	Egypt	-	323	459	140
6	Florida	1030	1370	1140	130
7	Australia	-	-	500	10
8	Sweden	-	-	15	390

Table 2. Portable device measurements of pollution rate, exposure, and location coordinates.

No	Radeye		Site name	No	Radeye		Site name
	C/s	Sv/hµ			C/s	Sv/hµ	
1	96	0.2	Phosphoric gypsum piles	1	12	0.02	housing complex
2	100	0.18		2	11	0.03	
3	106	0.2		3	10	0.03	
4	110	0.23		4	13	0.04	
5	102	0.19		5	12	0.02	
6	106	0.2		6	12	0.02	
7	96	0.22		7	13	0.03	
8	108	0.23		8	10	0.02	
9	102	0.2		9	13	0.02	
10	112	0.2		10	11	0.04	

Table 3. Concentrations of radionuclides in Bq /Kg in (Pg) phosphogypsum samples

Sample number	Th-234	Ra-226	Pb-214	Bi-214
Pg1	148.9±12.4	522.8±11.3	308.5±6.7	399.2±5.4
Pg2	147.1±13.7	640.8±12.3	378.1±7.3	488.6±6.2
Pg3	142.2±12.2	595.71±1.7	361.2±6.4	410.6±5.3
Pg4	137.4±11.1	497.8±2.1	302±4.3	374.12±4.2
Pg5	139.3±12.1	567.5±1.8	342.1±3.9	433.4±3.9
Pg6	140.2±13.2	582.41±1.3	353.1±1.2	405.4±2.7
Pg7	157.3±13.7	602.1±3.7	392±2.4	501.1±3.1
Pg8	151.4±11.2	503.2±3.4	381.3±1.3	441.3±4.5
Pg9	143.3±10.3	493.7±2.8	312.4±2.1	397.5±1.3
Pg10	136.2±9.1	463.2±1.9	334.2±1.3	437.2±2.1



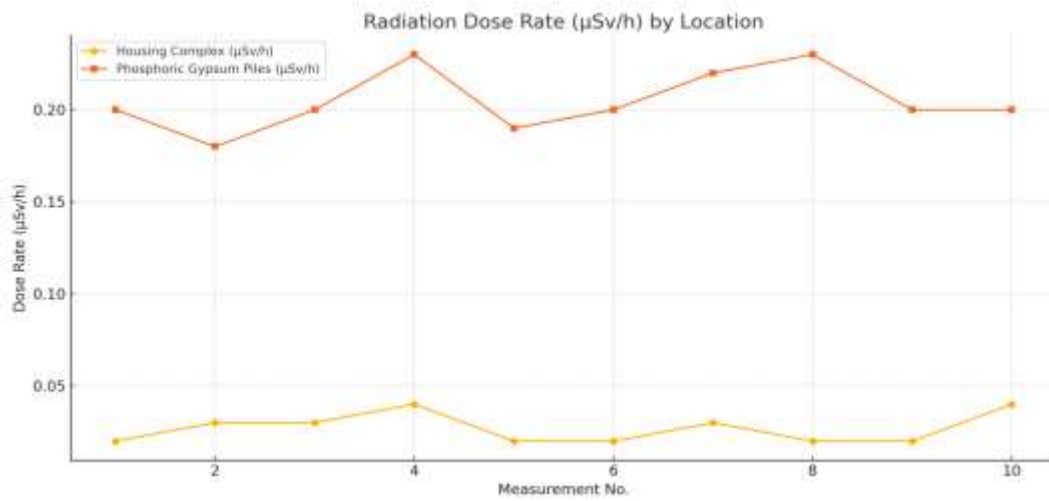
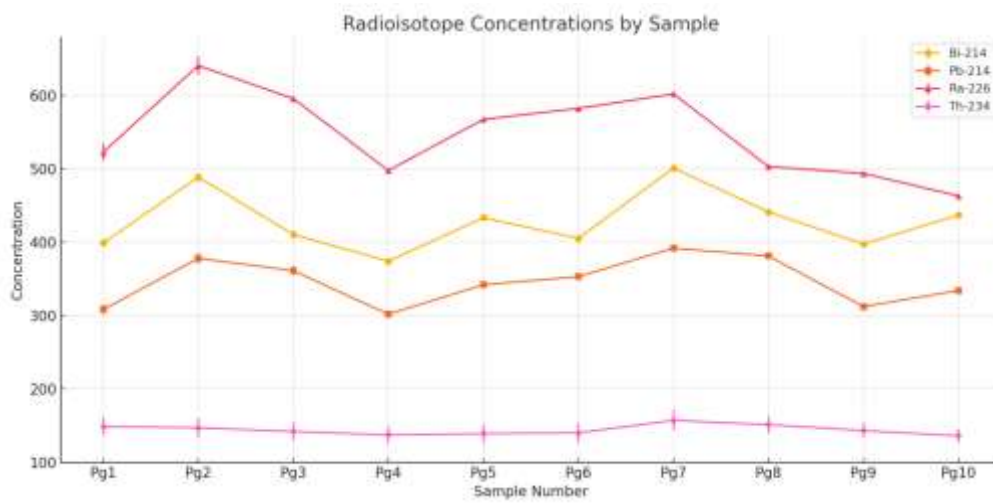


Figure 3. The graph comparing the average pain readings (µSv/h) between the residential complex (residential complex) and gypsum phosphate piles (gypsum phosphorous piles) locations for each measurement from 1 to 10



Bq/kg

Figure 4. Graph showing the concentrations of radionuclides in Bq/kg in phosphogypsum (Pg) samples.

4.2. DISCUSSION

The mean activity concentration of ^{226}Ra (640.8 ± 12.3 Bq/kg) exceeds the typical exemption levels for naturally occurring radionuclides in building materials. When compared with international reference values:

- The European Basic Safety Standards (EU-BSS) exemption level for ^{226}Ra in bulk amounts is 1000 Bq/kg, placing our samples below this threshold but indicating the need for radiological monitoring.
- The radium equivalent activity (Raeq), calculated using the formula $\text{Raeq} = \text{ARa} + (\text{ATh} \times 1.43) + (\text{AK} \times 0.077)$, should be evaluated against the recommended limit of 370 Bq/kg for materials used in construction without restrictions [4]. Our preliminary Raeq calculation (to be completed with Th and K data) will determine whether this material meets international building material criteria.
- The activity concentration index (I) for building materials, as defined in European Commission Radiation Protection Report 112, requires consideration if the material is intended for reuse.

Table 4. Comparison of radium-226 activity in phosphogypsum between different countries

Country/Region	^{226}Ra Activity (Bq/kg)	Reference	Year
Iraq (this study)	640.8 ± 12.3	Present study	2024
Romania	820 - 5278	Blebea-Apostu et al. [9]	2025
Senegal	532.3 (Raeq)	Modou et al. [4]	2024
Kosovo	up to 350 ± 30	Krasniqi et al. [5]	2025
Egypt	250 - 600	[7]	update year)
Jordan	~580	[8]	update year)
Global range	15 - 1140	Various [8]	-
USA (Florida)	850 - 1100	Hill et al. [8]	2025
Spain	600 - 800	Guillén et al. [7]	2025

The ^{226}Ra activity concentration measured in this study (640.8 Bq/kg) falls within the middle-to-upper range of global values reported in recent literature. It is comparable to values from Spanish phosphogypsum (600-800 Bq/kg) [7] and higher than those reported in Kosovo (350 Bq/kg) [5] and Senegal (532 Bq/kg) [4]. However, it is substantially lower than the extreme values reported in Romanian hot spots (up to 5278 Bq/kg) [9] and within the range of US phosphogypsum (850-1100 Bq/kg) [8]. This variation reflects differences in the geological origin of phosphate rocks sedimentary phosphates typically contain higher radionuclide concentrations than igneous sources [8], and the specific processing conditions at each facility.

The environmental implications of these findings are multi-faceted:

Storage and Management: Phosphogypsum stacks at the Akashat facility contain elevated ^{226}Ra concentrations, which may pose long-term radiological exposure risks through external gamma radiation, radon exhalation, and potential leaching into groundwater [4, 5, 9]. The measured activity levels suggest that these stacks require regular radiological monitoring and appropriate management strategies to minimize environmental impact.

Potential for Reuse: International interest in phosphogypsum reuse as a soil amendment [7] or building material [4] requires careful radiological assessment. The concentration of radium-226 in Iraqi phosphogypsum exceeds the guideline limit of 370 becquerels/kg of radium equivalent recommended for unrestricted use in building materials in some regions. [4]. Therefore, any consideration of phosphogypsum reuse should include a thorough radiological risk assessment and may require blending with other materials to reduce activity concentrations. **Public Health Considerations:** While direct public exposure is limited at the remote Akashat site, occupational exposure for workers handling phosphogypsum should be evaluated. The annual effective dose for workers should be calculated based on the measured activity concentrations and compared to the ICRP- recommended limit of 1 mSv/y for public exposure [4]. **Regulatory Framework:** These results provide Iraqi regulatory authorities with the first local data to develop national guidelines for TENORM management,

aligning with International Atomic Energy Agency safety standards and recommendations [1]. A consistent spread of radioactivity across the samples is reflected by the graph. The main isotope, Ra-226, source suggests a uranium- or radium-rich source.

Results of the present study were compared with international limits and recommendations made by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the International Atomic Energy Agency (IAEA). It can therefore be inferred that radiation exposure rates at phosphogypsum collection sites measured values between 0.20 and 0.21 $\mu\text{Sv/h}$, which are within permissible limits for general public radiation exposure (1 mSv/y) when converted into equivalent annual dose but much higher than natural background radiation levels in the area.

International bodies such as the International Atomic Energy Agency (IAEA), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and the Iraqi Radioactive Sources Control Authority adopt the concentration of the Ra-226 isotope as a reference indicator for assessing NORM-containing materials. The guideline value of 1000 Bq/kg is used for radiological assessment and regulatory action when necessary.

5. CONCLUSION

According to the results from this analysis, the activity concentration of radionuclides present in phosphogypsum manufactured by the General Company of Phosphate had a mean (average) concentration of radium-226, measuring 640.8 ± 12.3 Bq/kg; this value is also consistent with values found in other similar studies published worldwide. The results show that both the radiological and chemical aspects of this material are consistent with global information and do not exceed the universally accepted limits of safety. The construction of the radiological markers for the phosphogypsum produced in this facility establishes that, from a radiological standpoint, it can be placed into the "safe" category according to internationally accepted standards.

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BIOGRAPHIES OF AUTHORS

	<p>Mazen Abbas Katea Al-Gharrawy He received B.Sc. degree in Physics from Al-Mustansiriya University, Baghdad, Iraq, and a Master of Science degree in Nanophysics. He currently works as a Senior Chief Physicist and Radiation Protection Officer at the Iraqi Atomic Energy Commission. His research interests include environmental radioactivity, naturally occurring radioactive materials (NORM), and applications of nanomaterials in the field of radiation. He can be contacted at email: mazenkate5791@gmail.com https://orcid.org/0009-0008-7681-4488</p>
	<p>Ibtihal Abduljaleel Al-Rubaye She received B.Sc. degree in Chemistry from the University of Baghdad and a Master of Science degree in Analytical Chemistry. She is the head of the Chemists Department at the Scientific Research Authority, specializing in analytical chemistry and nanomaterials research, and has experience working with specialized laboratory equipment. Baghdad, Iraq.</p>
	<p>Zaki Abduljabbar Alqaisi He received Diploma in Health Physics, Technical Education Authority and B.Sc. degree in physics University of Baghdad. He works as a senior chief physicist at the Iraqi Atomic Energy Commission, where he is responsible for radiometric measurements. His research interests include radiometric measurements, gamma-ray spectroscopy, and the evaluation of naturally occurring radioactive materials (NORM), Baghdad, Iraq. email: alqaisy@yahoo.com_zeki</p>