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Characterization of Phosphogypsum from Cartagena and Huelva, Spain

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Abstract: Phosphogypsum (PG), a by-product of phosphoric acid production, is recognized as a Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) due to its enrichment in uranium-series radionuclides. In Spain, particularly in Huelva and Cartagena, large PG stacks raise growing environmental concerns related to soil and groundwater contamination. This study presents a mineralogical and preliminary environmental assessment of PG samples from these regions using X-ray diffraction (XRD) and energy-dispersive X-ray fluorescence (EDXRF). Gypsum ($CaSO_4 \cdot 2\,H_2O$) was identified as the dominant crystalline phase in all samples. Variations in peak intensity and preferred orientation suggest mineralogical heterogeneity linked to source rock properties and processing conditions. Subtle peak shifts and broadening indicate co-hydration with H_2O and D_2O, consistent with isotopic fractionation during crystallization. EDXRF analysis also revealed the presence of heavy metals such as chromium (Cr), nickel (Ni), lead (Pb), and zinc (Zn), as well as trace elements like strontium (Sr) and barium (Ba), which may influence environmental risk. No discrete phases of uranium, thorium, or radium were detected by XRD, supporting their probable incorporation at trace levels through substitution or adsorption, a finding confirmed by EDXRF elemental analysis. This mineralogical and chemical data forms the baseline from which a further comprehensive material characterization will be drawn, integrating gamma spectrometry, ICP-MS and SEM to evaluate the chemical speciation and environmental risk of PG. Based on Web of Science data, over 300 peer-reviewed articles on PG were published globally between 2020 and 2025, with China, Morocco, and Brazil leading in scientific output. The growing research interest underscores the strategic relevance of detailed PG characterization for informing safe reuse, regulatory decisions, and circular economy applications.

Keywords: Phosphogypsum, X-ray Diffraction, TENORM.

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Caracterização do Fosfogesso de Cartagena e Huelva, Espanha

Resumo: O fosfogesso (PG), subproduto da produção de ácido fosfórico, é reconhecido como um Material Radioativo Naturalmente Ocorrente com Tecnologia Aprimorada (TENORM) devido ao seu enriquecimento em radionuclídeos da série do urânio. Na Espanha, particularmente em Huelva e Cartagena, grandes pilhas de PG levantam crescentes preocupações ambientais relacionadas à contaminação do solo e da água subterrânea. Este estudo apresenta uma avaliação mineralógica e ambiental preliminar de amostras de PG dessas regiões, utilizando difração de raios X (DRX) e fluorescência de raios X por energia dispersiva (EDXRF). O gesso ($CaSO_4 \cdot 2\ H_2O$) foi identificado como a fase cristalina dominante em todas as amostras. Variações na intensidade dos picos e na orientação preferencial sugerem heterogeneidade mineralógica ligada às propriedades da rocha de origem e às condições de processamento. Deslocamentos sutis e alargamento dos picos indicam cohidratação com H_2O e D_2O, consistente com fracionamento isotópico durante a cristalização. A análise por EDXRF também revelou a presença de metais pesados como cromo (Cr), níquel (Ni), chumbo (Pb) e zinco (Zn), além de elementos-traço como estrôncio (Sr) e bário (Ba), que podem influenciar o risco ambiental. Nenhuma fase discreta de urânio, tório ou rádio foi detectada por DRX, corroborando sua provável incorporação em níveis traço por substituição ou adsorção, confirmação obtida pela análise elementar por EDXRF. Os dados mineralógicos e químicos obtidos constituem uma base de referência essencial para subsidiar etapas futuras de caracterização mais detalhada e abrangente do material, nas quais serão integradas a espectrometria gama, o ICP-MS e o SEM, com o objetivo de avaliar a especiação química e o risco ambiental associado ao fosfogesso (PG). Segundo dados da Web of Science, mais de 300 artigos revisados por pares sobre PG foram publicados globalmente entre 2020 e 2025, com China, Marrocos e Brasil liderando a produção científica. O crescente interesse na pesquisa destaca a relevância estratégica da caracterização detalhada do PG para orientar o reuso seguro, decisões regulatórias e aplicações na economia circular.

Palavras-chave: Fosfogesso, Difração de Raios X, TENORM.

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Caracterización del Fosfogeso de Cartagena y Huelva, España

Resumen: El fosfogeso (PG), subproducto de la producción de ácido fosfórico, es reconocido como un Material Radioactivo Naturalmente Ocorrente con Tecnología Mejorada (TENORM) debido a su enriquecimiento en radionucleidos de la serie del uranio. En España, particularmente en Huelva y Cartagena, grandes pilas de PG generan crecientes preocupaciones ambientales relacionadas con la contaminación del suelo y del agua subterránea. Este estudio presenta una evaluación mineralógica y ambiental preliminar de muestras de PG de estas regiones, utilizando difracción de rayos X (DRX) y fluorescencia de rayos X por dispersión de energía (EDXRF). El yeso ($CaSO_4 \cdot 2\ H_2O$) fue identificado como la fase cristalina dominante en todas las muestras. Variaciones en la intensidad de los picos y en la orientación preferencial sugieren heterogeneidad mineralógica vinculada a las propiedades de la roca fuente y a las condiciones de procesamiento. Desplazamientos sutiles y ensanchamiento de los picos indican cohidratación con H_2O y D_2O, consistente con fraccionamiento isotópico durante la cristalización. El análisis por EDXRF también reveló la presencia de metales pesados como cromo (Cr), níquel (Ni), plomo (Pb) y zinc (Zn), así como elementos traza como estroncio (Sr) y bario (Ba), que pueden influir en el riesgo ambiental. No se detectaron fases discretas de uranio, torio o radio mediante DRX, lo que respalda su probable incorporación a niveles traza por sustitución o adsorción, hallazgo confirmado por el análisis elemental por EDXRF. Los datos mineralógicos y químicos obtenidos constituyen una base de referencia esencial para sustentar etapas futuras de caracterización más detallada e integral del material, en las cuales se integrarán la espectrometría gamma, el ICP-MS y el SEM, con el fin de evaluar la especiación química y el riesgo ambiental asociado al fosfoyeso (PG). Según datos de Web of Science, se publicaron más de 300 artículos revisados por pares sobre PG a nivel mundial entre 2020 y 2025, con China, Marruecos y Brasil liderando la producción científica. El creciente interés en la investigación subraya la relevancia estratégica de una caracterización detallada del PG para orientar la reutilización segura, las decisiones regulatorias y las aplicaciones en economía circular.

Palabras clave: Fosfoyeso, Difracción de Rayos X, TENORM.

1. INTRODUCTION

Phosphogypsum (PG, $CaSO_4 \cdot 2\,H_2O$) is a major industrial by-product generated during the production of phosphoric acid via the wet sulfuric acid process. For every ton of phosphoric acid produced, approximately four to five tons of PG are generated [1]. This quantity of material presents not only logistical challenges for disposal and storage, but also environmental concerns due to the presence of contaminants. PG is classified as a Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) because it concentrates radionuclides from the decay series of uranium (^{238}U) and thorium (^{232}Th), along with trace amounts of heavy metals and fluorides [2;3].

In Spain, the most significant PG deposits are found in Huelva and Cartagena. The Huelva site alone contains over 120 million tons of PG spread across 1,200 hectares [4]. These materials are typically stored in open-air stacks, which are vulnerable to atmospheric exposure, weathering, and leaching processes that can mobilize contaminants into surrounding soils and groundwater systems [3;5]. The chemical and mineralogical composition of PG is largely influenced by the origin of the phosphate rock and the operational parameters of the production process [1;6].

Given the presence of hazardous impurities, a comprehensive understanding of the structural, chemical, and radiological characteristics of PG is essential for environmental risk assessment and for identifying safe pathways for reuse. X-ray diffraction (XRD) plays a critical role in elucidating the mineralogical composition, especially in identifying the primary crystalline phases such as gypsum. However, XRD alone cannot detect trace contaminants or amorphous phases [7;8], which necessitates the integration of complementary analytical techniques including energy-dispersive X-ray fluorescence (EDXRF), gamma spectrometry, inductively coupled plasma mass spectrometry (ICP-MS), and microscopy-based methods.

Addressing this issue involves repurposing this waste into a valuable resource with potential applications in agriculture [9;2;10], construction [2;11], CO_2 capture [12], among others. To explore these possibilities, the characterization of phosphogypsum stacks is crucial, encompassing an analysis of their composition, impurities, and radioactivity.

A recent bibliometric survey in Web of Science Database identified 301 scientific articles published between 2020 and 2025 that specifically address PG [13]. Research efforts are concentrated in countries with large fertilizer industries and active regulatory agendas, particularly China, Morocco, and Brazil [13]. This growing international interest reflects the urgency in understanding PG behavior and exploring its potential for safe valorization within circular economy frameworks.

This study provides a comprehensive mineralogical and chemical baseline for phosphogypsum (PG) from Cartagena and Huelva, integrating hydration states and crystallographic variations identified by X-ray diffraction (XRD) with elemental composition determined by energy-dispersive X-ray fluorescence (EDXRF). These combined results establish a solid foundation for subsequent chemical and radiological investigations aimed at evaluating the reuse potential and environmental impact of PG across diverse technological applications.

2. MATERIALS AND METHODS

The phosphogypsum samples were collected from two different regions, Cartagena (C1 and C2) and Huelva (H), in Spain. The samples underwent a series of preparation steps: drying in an oven at 50°C, homogenization, quartering, grinding in an agate mortar, and sieving to 200 mesh. For XRD analyses, the phosphogypsum was measured in a zero-background holder spinning in 4 seconds, using a diffractometer with a copper anode (Empyrean/Malvern Panalytical in LabCri/UFMG) in a theta-2theta configuration. The X-ray source operated at 45 kV and 40 mA, coupled with a BBHD mirror, knife, 1/8°

divergence slit, 1/16° anti-scatter slit, mask 10mm, 0.04 rad soller slits, and the pixel 2x2 detector worked with a 16.8 anti-scatter slit, 0.04 rad large soller slits, and nickel filter.

Elemental analyses of the powdered samples were performed using an energy-dispersive X-ray fluorescence (EDXRF) spectrometer (Rigaku NEX CG in LFA/CDTN). Each sample was analyzed in quadruplicate to ensure measurement repeatability. Quantification was performed using the RPF-SQX fundamental parameters software. The instrument allows detection of elements from Na to U, with detection limits reaching the low ppm level. For quality control, results with relative standard deviation (RSD%) greater than 15% were considered below the lower limit of detection (<LLD) and therefore not reported.

3. RESULTS AND DISCUSSIONS

3.1. Crystalline Phases and Hydration Behavior

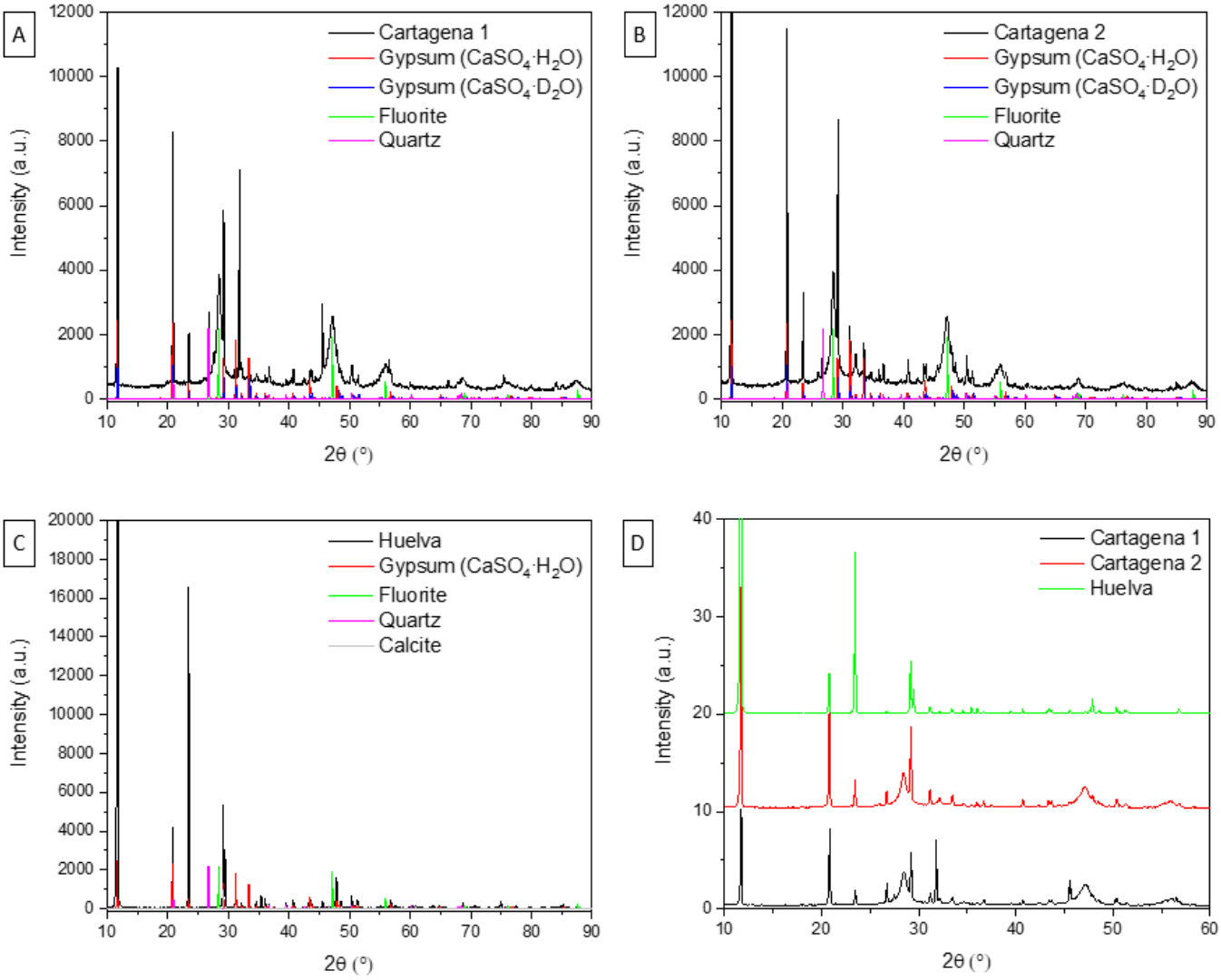
XRD analysis confirmed the presence of calcium sulfate dihydrate (gypsum, $CaSO_4 \cdot 2\,H_2O$) as the dominant crystalline phase in all phosphogypsum samples from Cartagena and Huelva. Despite this mineralogical consistency, the diffractograms revealed notable variations in peak intensities and relative reflection dominance, indicating differences in preferred crystallographic orientation and possibly in grain morphology.

The sample from Cartagena (zone 1) exhibited a prominent reflection at $2\theta \approx 45.5°$, attributed to the (170) plane of gypsum, whereas the Huelva sample showed more intense peaks at $2\theta \approx 11.6°$ and 23.4°, corresponding to the (020) and (040) planes, respectively. These differences may be associated with the depositional environment, crystallization kinetics, or physical stacking and weathering conditions [1].

Additionally, detailed inspection of the region between 20° and 23° (2θ) revealed subtle peak shifts and broadening, consistent with hydration heterogeneity. These features

suggest co-existence of water (H_2O) and deuterated water (D_2O) in the gypsum structure, likely resulting from isotopic fractionation during precipitation, a phenomenon previously reported in PG samples exposed to variable hydrochemical conditions [6].

Figure 1: XRD measurements of Cartagena and Huelva, Spain. (A) Cartagena zone 1 measured XRD pattern; (B) Cartagena zone 2 measured XRD pattern; (C) Huelva measured XRD pattern; (D) Comparison of XRD patterns from Cartagena 1 and Cartagena 2 and Huelva



The overlaid XRD patterns of the three samples (Figure 1-D) reveal a high degree of mineralogical similarity between the Cartagena samples, as indicated by their nearly identical peak positions and relative intensities. In contrast, the Huelva sample displays subtle differences in the relative intensities of certain reflections, suggesting minor variations in

composition or crystallinity. All samples confirm the presence of gypsum ($CaSO_4 \cdot 2\ H_2O$) as the main phase, with quartz (SiO_2) and fluorite (CaF_2) as secondary components. Additionally, the Cartagena samples (C1 and C2) show diffraction features consistent with the presence of deuterated water (D_2O) in the gypsum structure, while the Huelva sample exhibits reflections attributed to calcium carbonate ($CaCO_3$), further supporting its mineralogical distinction.

3.2. Elemental analysis using EDXRF

The elemental composition obtained by EDXRF complements the mineralogical characterization by XRD and allows for quantitative estimation of the main crystalline phases present in the phosphogypsum samples from Cartagena (C1 and C2) and Huelva (H). It is important to highlight that the oxygen content measured by EDXRF is estimated indirectly, as this technique cannot detect elements lighter than sodium. Therefore, the reported oxygen values may include contributions from undetected light elements below the detection limit, and this should be considered when interpreting the data.

Table 1: EDXRF analysis results of major elements

	Ca		S		O			
Samples	**mass %**	**std dev.**	**mass %**	**std dev.**	**mass %**	**std dev.**		
C1	20.4	0.1	2.18	0.02	67.16	0.26		
C2	20.3	0.1	2.65	0.02	67.39	0.14		
H	26.3	0.1	14.0	0.1	57.05	0.17		
	Si		**P**		**Cl**		**Fe**	
Samples	**mass %**	**std dev.**	**mass %**	**std dev.**	**mass %**	**std dev.**	**mass %**	**std dev.**
C1	3.39	0.02	1.81	0.02	3.80	0.02	0.645	0.011
C2	2.01	0.03	1.96	0.01	4.95	0.02	0.366	0.005
H	1.48	0.01	0.271	0.006	0.184	0.003	0.370	0.007

Table 2: EDXRF analysis results of trace hazardous elements

	As		Ba		Cr		Ni	
Samples	**ppm**	**std dev.**	**ppm**	**std dev.**	**ppm**	**std dev.**	**ppm**	**std dev.**
C1	<LLD		60	6	611	23	320	7
C2	13.0	1.0	60	3	327	5	169	3
H	27	3	244	10	90	9	29	2
	Pb		**Sr**		**V**		**W**	
Samples	**ppm**	**std dev.**	**ppm**	**std dev.**	**ppm**	**std dev.**	**ppm**	**std dev.**
C1	133	2	127	2	517	22	21	2
C2	30.0	1.1	175	7	300	26	21	2
H	42	3	705	14	<LLD		<LLD	
	Zn		**Zr**					
Samples	**ppm**	**std dev.**	**ppm**	**std dev.**				
C1	331	7	399	10				
C2	168.0	1.2	380	22				
H	20.0	1.1	638	19				

<LLD for all samples: Ag, Bi, Cd, Co, Cu, Ga, Hg, In, Mn, Mo, Nb, Sb, Sn and Tl.

Table 3: EDXRF analysis results of radioactive elements and rare earth elements

	U		Th		Gd		Y	
Samples	**ppm**	**std dev.**	**ppm**	**std dev.**	**ppm**	**std dev.**	**ppm**	**std dev.**
C1	135.0	1.2	14	1.1	261	7	667	5
C2	165	8	19.0	0.9	<LLD		678	32
H	30	2	<LLD		<LLD		189	4

<LLD for all samples: Ce, Eu, La, Nd and Pr.

Based on elemental data obtained by EDXRF (Table 1, Table 2 and Tabel 3) and phase identification by XRD, qualitative differences in the mineralogical composition of the samples were observed. Samples C1 and C2 (Cartagena) exhibit a lower Ca/S ratio, which aligns with the presence of gypsum ($CaSO_4 \cdot 2H_2O$) as the main sulfur-bearing phase, and suggests that part of the calcium is also present as calcium fluoride (CaF_2), consistent with the crystalline phases detected by XRD. In contrast, sample H (Huelva) shows a higher Ca/S ratio, which, together with the XRD identification of calcium carbonate ($CaCO_3$), indicates

that calcium in this sample is distributed among gypsum, CaF_2, and $CaCO_3$. Additionally, the lower silicon and phosphorus contents in H observed by EDXRF suggest reduced amounts of quartz (SiO_2) and phosphate-related species compared to C1 and C2. These compositional and mineralogical differences reflect distinct processing or environmental conditions influencing the phosphogypsum deposits from Cartagena and Huelva.

Trace element analysis confirmed the presence of uranium (U) in all samples, with the highest concentration in C2 (165 ppm), and thorium (Th) was detected only in C1 and C2 (14–19 ppm), as shown in Table 3. These results corroborate the classification of phosphogypsum as a Technologically Enhanced Naturally Occurring Radioactive Material (TENORM), emphasizing the need for further detailed radiological investigations due to the long half-life of these radionuclides.

3.3. Absence of Crystalline Radioactive Phases

No discrete crystalline phases containing uranium, thorium, or radium were detected by XRD in any of the samples. This absence does not imply that these radionuclides are not present; rather, it suggests that they are incorporated into the gypsum matrix as trace dopants or adsorbed onto amorphous or nanocrystalline phases. This interpretation is supported by prior studies using gamma spectrometry and ICP-MS [3;5], as well as by the present EDXRF analysis, which confirmed the presence of uranium in all samples and thorium only in samples Cartagena samples.

Lütke et al. [7] demonstrated that nanocrystalline and amorphous structures – undetectable by XRD – can host significant quantities of radionuclides, further highlighting the necessity for advanced microscopic and spectrometric analyses to fully characterize these materials.

3.4. Environmental Risk and Multi-Technique Characterization

The environmental risk associated with PG extends beyond its radionuclide content. Literature reports, including those focused on Brazilian and North African PG, indicate the frequent presence of trace metals such as Sr, Ba, Pb, and rare earth elements [8]. These elements may substitute for calcium in the gypsum lattice or bind within secondary mineral phases, potentially affecting their leachability and long-term environmental mobility. Trace metals such as strontium (Sr), barium (Ba), lead (Pb), chromium (Cr), nickel (Ni), and zinc (Zn) were detected at varying concentrations, as shown in Table 2, with Sr and Ba notably enriched in the Huelva sample (705 ppm and 244 ppm, respectively). These elements, together with rare earth elements (REE) like gadolinium (Gd) and yttrium (Y), and radioactive elements uranium (U) and thorium (Th) (Table 3), can substitute calcium within the gypsum lattice or associate with secondary mineral phases. Such incorporation can influence their leachability and long-term mobility in the environment, impacting soil and groundwater quality.

The analysis showed that other hazardous trace elements, such as arsenic (As), chromium (Cr), nickel (Ni), and lead (Pb), were found at higher concentrations in Cartagena (C1), whereas Huelva had comparatively lower levels, except for Sr and Ba.

Given this complex elemental distribution and the coexistence of radionuclides and trace metals, a comprehensive evaluation of environmental risks requires a multi-technique approach. Techniques such as gamma spectrometry, inductively coupled plasma mass spectrometry (ICP-MS), and scanning electron microscopy (SEM) are essential for elucidating elemental associations, chemical speciation, and the morphological contexts of contaminant retention. These complementary methods will enable a more detailed understanding of contaminant behavior, contributing to safer management and potential reuse strategies for phosphogypsum wastes.

4. CONCLUSIONS

X-ray diffraction analysis confirmed that gypsum ($CaSO_4 \cdot 2\,H_2O$) is the dominant crystalline phase in phosphogypsum samples from Cartagena and Huelva. Variations in peak intensities and preferred crystallographic orientations indicate structural heterogeneities likely influenced by source material, processing conditions, and environmental exposure. Observed hydration patterns, including indications of deuterated water (D_2O), suggest isotopic variability within the gypsum structure, which may have important implications for the mechanical and chemical stability of phosphogypsum in reuse scenarios.

The presence of calcium fluoride (CaF_2) in all samples and calcium carbonate ($CaCO_3$) specifically in the Huelva sample was evidenced by XRD and supported by elemental composition data obtained via EDXRF. Differences in calcium-to-sulfur ratios and silicon and phosphorus contents further reflect distinct mineralogical and chemical characteristics between the two phosphogypsum deposits.

Although no discrete crystalline phases containing uranium, thorium, or radium were detected by XRD, EDXRF analysis confirmed the presence of uranium in all samples and thorium in Cartagena samples, consistent with their incorporation into the gypsum matrix as trace dopants or adsorption onto amorphous phases. These results underscore the limitations of XRD for detecting trace contaminants and highlight the necessity of complementary analytical techniques.

This mineralogical and chemical baseline provides essential information for the ongoing multidisciplinary assessment of Spanish phosphogypsum. To comprehensively evaluate environmental risks and valorization potential, further characterization will involve gamma spectrometry, inductively coupled plasma mass spectrometry (ICP-MS), and scanning electron microscopy (SEM) to elucidate elemental speciation, mobility, and bioavailability of hazardous elements.

The integrative approach outlined here aligns with international efforts to promote sustainable management of industrial by-products and supports circular economy strategies aimed at minimizing environmental impact while unlocking safe reuse opportunities for phosphogypsum.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

REFERENCES

[1] AKFAS, F. *et al.* Exploring the potential reuse of phosphogypsum: A waste or a resource?. **Science of the Total Environment**, v. 908, 168196, 2024.

[2] MAZZILLI, B. *et al.* Radiochemical characterization of Brazilian phosphogypsum. **Journal of Environmental Radioactivity**, v. 49, p. 113-122, 2000.

[3] GENNARI, R. F. *et al.* Phosphogypsum analysis: total content and Extractable element concentrations. In: **Anais do INAC 2011 – International Nuclear Atlantic Conference**, Belo Horizonte, MG, Brasil, 2011.

[4] GUERRERO, J. L. *et al.* Pollution evaluation on the salt-marshes under the phosphogypsum stacks of Huelva due to deep leachates. **Chemosphere**, v. 230, p. 219-229, 2019.

[5] MOREIRA, R. H. *et al.* Extraction of natural radionuclides in TENORM waste phosphogypsum. **Journal of Environmental Chemical Engineering**, v. 6, n. 5, p. 6664-6668, 2018.

[6] LIU, T.; *et al.* Prediction of equilibrium isotopic fractionation of the gypsum/bassanite/water system using first-principles calculations. **Geochimica et Cosmochimica Acta**, v. 244, p. 1-11, 1 jan. 2019.

[7] LÜTKE, S. F. *et al.* Leaching of rare earth elements from phosphogypsum. **Chemosphere**, v. 301, 134661, 2022.

[8] SANTOS, A. J. G. et al. Partitioning of radionuclides and trace elements in phosphogyosum and its source materials based on sequential extraction methods. **Journal of Environmental Radioactivity**, v. 87, n. 1, p. 52-61, 2006.

[9] RENTERÍA-VILLALOBOS, M. *et al.* Radiological, chemical and morphological characterizations of phosphate rock and phosphogypsum from phosphoric acid factories in SW Spain. **Journal of Hazardous Materials**, v. 181, n. 1–3, p. 193–203, set. 2010.

[10] BORGES, R. C. *et al.* Radioactive characterization of phosphogypsum from Imbituba, Brazil. **Journal of Environmental Radioactivity**, v. 126, p. 188–195, dez. 2013.

[11] COSTA, R. P. *et al.* Effect of soluble phosphate, fluoride, and pH in Brazilian phosphogypsum used as setting retarder on Portland cement hydration. **Case Studies in Construction Materials**, v. 17, 1 dez. 2022.

[12] VALDEZ-CASTRO, L. et al. Capture of CO2 through phosphogypsum and lye residues from the olive industry. **Journal of CO2 Utilization**, v. 72, 1 jun. 2023.

[13] WEB OF SCIENCE. Publicações sobre fosfogesso (2020–2025). **Web of Science Core Collection**. Clarivate Analytics. Disponível em: https://www.webofscience.com. Accessed on June 10, 2025.

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