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Sustainable Reuse of Algerian Black Phosphate Mining Tailings to Recover P_2O_5

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Abstract

The Djebel Onk region of Algeria faces a significant environmental concern, related to phosphate mining waste. Although these mining tailings contain relatively low quantities of valuable minerals, they still include up to 25% P_2O_5 in the particle size range of 0.25-1 mm (-1-+0.25), suggesting the potential for recovery and reuse. This research, based on the Bir El Ater area, explores the methods to recover phosphate-rich minerals, optimizing their reuse. Two techniques were explored: calcination, a heat treatment altering mineral chemistry, and electrostatic separation, which uses the electrical properties to separate minerals. The black phosphate tailings collected from the curved grids of wet processing were subjected to detailed analysis using Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), and X-Ray Fluorescence (XRF), to examine their mineralogical and chemical properties. The results showed a notable improvement in the P_2O_5 concentration, with electrostatic separation reaching a 30.03% content and an 89% recovery rate, while calcination achieved the 30.91% content with a 91% recovery rate. These results highlight the effectiveness of both methods in recovering phosphate from mining tailings, contributing to a better waste management, a more efficient resource use, and a reduced environmental footprint. They also suggest sustainable recovery pathways, especially for the regions facing water scarcity, where flotation is impractical. With the ability to achieve high recovery rates without chemical inputs, calcination and electrostatic separation stand out as environmentally sustainable options for global phosphate beneficiation.

1. Introduction

The handling of large-scale mining waste, generated by the industrial, open-pit, and underground mining methods, presents significant challenges, both economically and environmentally. Specifically, at the phosphate mining company SOMIPHOS (Société des Mines de Phosphates), the industry produces thousands of tons of phosphate tailings, which are stored on mine tiles. This storage technique occupies vast areas, leading to serious environmental issues for instance, phosphate tailing basins cause significant physical changes to the environment and a substantial ecological footprint in the mining site areas [1].

The tailings from the phosphate processing plants represent a primary secondary source of phosphate minerals that can be valorized, particularly rare earth elements, cement compounds, and other co-extracted metals [2]. To meet the specifications necessary for manufacturing a phosphate fertilizer, the quality of phosphate must adhere to certain industry

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standards [3–5]. These standards include the P_2O_5 content should be > 30 weight%, CaO/P_2O_5 ratio < 1.6 weight%, as well as the MgO content < 1 weight%. The most common phosphate minerals in ores are fluorapatites and carbonate-apatite, which contain a gangue of calcite, quartz, and dolomite. These minerals pose real challenges for phosphate enrichment, due to their similar physicochemical characteristics [6,7].

Various methods have long been used to concentrate phosphate in natural ores including flotation, calcination, acid leaching, and magnetic separation. However, these processes typically require large quantities of water. To reduce water consumption, alternative dry processes such as electrostatic separation, pneumatic separation, and calcination are employed [5,8].

Calcination decomposes carbonate materials at high temperatures, removing impurities and enhancing phosphate concentration at temperatures (850-1050 °C) to produce gas CaO, MgO and CO_2 in the phosphate mineral, though it is energy-intensive and generates phosphogypsum [9–13].

In semi-arid regions, electrostatic separation is used as a dry method to recover phosphate concentrates [14–16]. This method exploits electrical fields to separate charged mineral particles [17,18]. Tests on the Florida phosphate samples showed a P_2O_5 content of 30% with 85% recovery and a low MgO content. When a negative voltage is applied, dolomite acquires a negative charge, while phosphate becomes positively charged, with the charge disparity increasing as the voltage rises [19,20].

This study investigates the potential of calcination and electrostatic separation as methods for recovering phosphate from black phosphate tailings at Kef Essnoun, Djebel Onk (Tebessa, Algeria). The research aims to provide sustainable enrichment solutions for phosphate, particularly in the arid and semi-arid regions. The study assesses the efficiency of these methods in phosphate recovery, waste reduction, and environmental sustainability by analyzing the tailings' behavior during calcination and electrostatic separation. The overarching goal is to create the scalable phosphate recovery methods for SOMIPHOS in Algeria.

2. Materials and Methods

2.1. Geographical location of phosphate deposit

The study examines the Djebel Onk mining basin, which is found in the Tebessa region, approximately 20 km from the Algerian-Tunisian border and 600 km southeast of Algiers. (Figure 1). This deposit is situated to the east of the Nememcha Mountains in the northeastern region of the Algerian Sahara. The Djebel Onk mining factory, situated about two kilometers from the mining quarries, processes run-of-mine phosphate to increase the P_2O_5 content in the commercial product. At the Kef Essnoun deposit, a 35 m thick Upper Thanetian phosphorite layer is divided into three sub-layers across the Djebel Onk district, based on P_2O_5 and MgO content (Figure 2):

1) A 2-meter-thick basal sub-layer of alternating marl, phosphorite, and dolomite.

2) A 25–30-meter main sub-layer of mostly phosphorite with minor marl and dolomite.

3) An upper sub-layer of 1-10 meters consisting mainly of phosphatic dolomite with fewer phosphate particles.

2.2. Physicochemical characterization of samples

In this experimental study, representative samples of black phosphate tailings with a total mass of 50 kg were taken from the curved grid (+1 mm), and subjected to physiochemical characterization. The sampling was dried at 100 °C for 12 hours, homogenized, and grinded using a grinder type Retsch-RM 200 in the laboratory of the SOMIPHOS plant in Tebessa.

Dry sieve analysis operations was conducted at the Mineral Processing and Environmental Laboratory, University of Annaba, using an electro-vibrant Retsch-AS200 Basic sieve on 500 g samples. The vibratory amplitude was set to 80 mm, with a sieving duration of 20 minutes. The physicochemical analyses were conducted using X-Ray Fluorescence (XRF) (Bruker S8 TIGER) and X-Ray Diffraction (XRD) (PANalytical Empyrean). The results obtained from these instruments were processed with the software HighScore Plus. The chemical and mineralogical results were obtained at the level of advanced research and testing laboratories at Al-Hussein Bin Talal University in Jordan.

Scanning Electron Microscopy (SEM) observations and energy-dispersed X-ray spectrometry (EDS) analysis are performed at the SONATRACH DLAB STRATIGRAPHIE

Laboratory. Energy-dispersed X spectroscopy (EDS) has significant advantages over SEM because the EDS provides accurate and detailed information on the chemical composition and distribution of the elements of a sample [6,23].

The characterization by XRF, XRD, and SEM provides detailed information on the samples. So, XRF identifies and quantifies the chemical elements, XRD determines the crystal structure and mineral phases, and SEM, together with EDS, examines the morphology and elemental distribution on a microscopic scale.

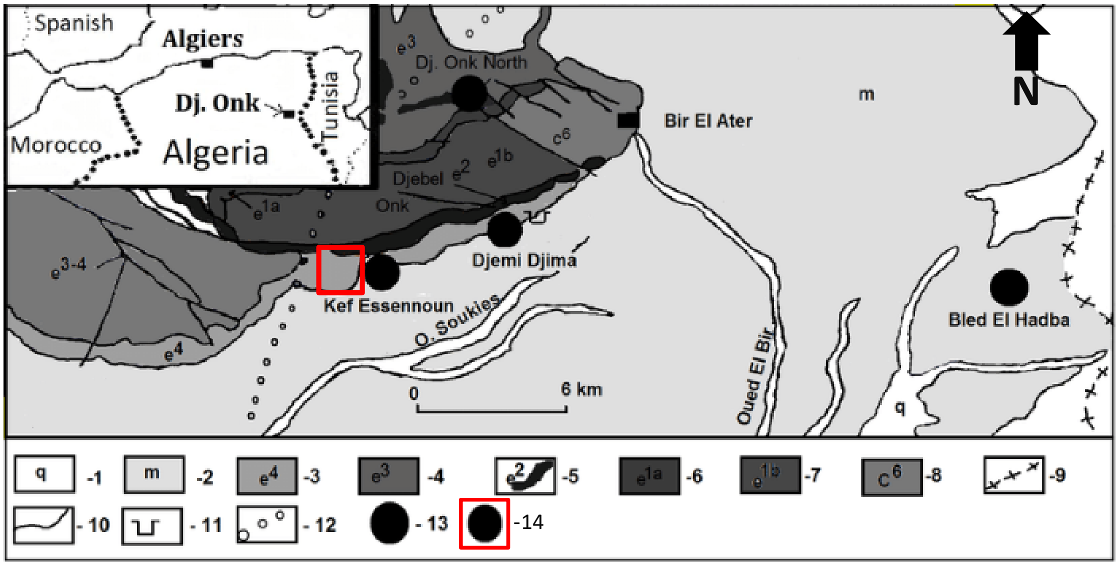

Figure 1. Geological schematic map showing the location and distribution of phosphate deposits in Djebel Onk [21]: 1 Silty alluvial deposits (Quaternary); 2 Sand and clay (Miocene); 3 Marl and limestone (Lutetian); 4 Marl and limestone with phosphate level (Ypresian); 5 Marl, limestone, dolomite and main phosphate layer Thanetian); 6 coquina limestone and marl (Montian); 7 Marl and limestone (Danian); 8 Limestone (Maastrichtian); 9 Algerian–Tunisian border; 10 Geological outline; 11 Djemi Djema open pit; 12 Shallow of Ain Fouris: western limit of the main phosphatic layer; 13 Phosphate deposit; 14 studied area.

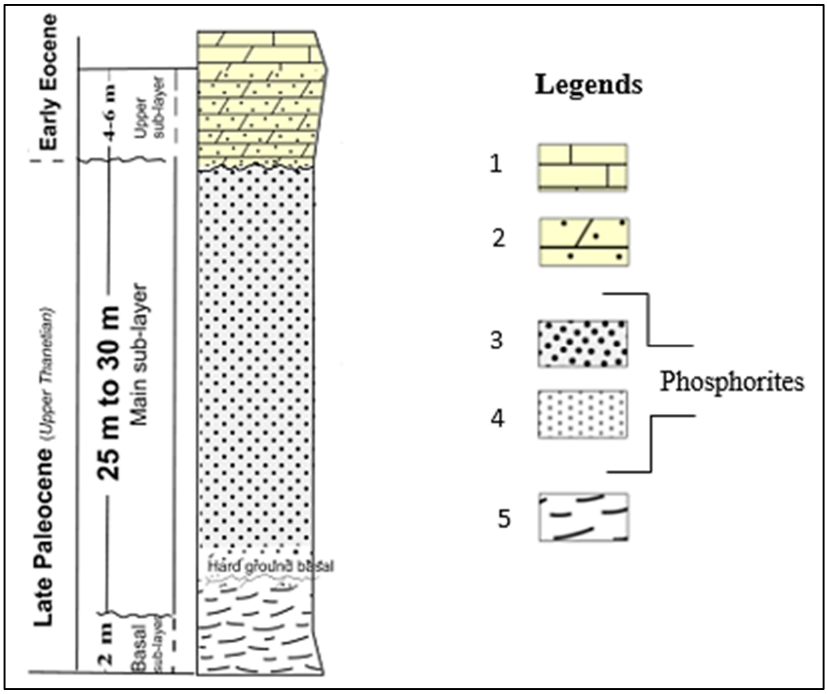

Figure 2. Simplified lithological columns with the sampled sections [22]. 1 – limestone; 2 – dolomitic phosphorites; 3 – coarse grained phosphorites; 4 – fine phosphorites; 5 –marl.

2.3. Beneficiation of black phosphate tailings by calcination and electrostatic separation

2.3.1. Calcination

Numerous studies on the influence of calcination temperature on porosity, reactivity, and surface specificity have shown a sharp decrease in these characteristics in a narrow range of temperatures [24–28].

In addition, mineral phosphate characterized by a high content of carbonates negatively affects the quality of the market product, which requires treatment to reduce these carbonates (dolomite and calcite) by a simple and effective method (calcination) [24]. Calcination is performed to thermally dissociate the carbonates from both the exogangue and endogangue within a temperature range of 700 to 1000 °C. To reduce the proportions of CaO and MgO, relative to P_2O_5, the second important step consists of an operation of hydration of the oxides of Ca and Mg to, then be able to remove them, then the mineral undergoes a washing, which consists in the removal of the alkaline salts (K_2O, Na_2O) and lime (CaO, MgO) either by dissolution or by suspension in the water without the entry of chemical reagents.

Calcination tests were conducted in the chemistry laboratory of the National Phosphate Enterprise (SOMIPHOS). These tests were performed on fractions (-1+0.125 mm) of the obtained concentrated product using a CARBOLITE muffle furnace, with a temperature increase of 15°C/min. Samples were calcined at temperatures of 850 °C, 950 °C, and 1050 °C for durations of 30 and 60 minutes to reduce the organic material content in the Kef Essenoun black phosphate tailings. After calcination, the samples were cooled, washed, and analyzed for the P_2O_5 and MgO content.

2.3.2. Electrostatic separation

Since 1940, the researchers have been exploring ways to enhance the phosphate mineral recovery through dry-track electrostatic separation, a promising alternative to water-dependent methods that face high flotation costs and water treatment difficulties [8]. Electrostatic separation takes advantage of differences in electrical conductivity between materials to separate them. It is commonly applied to minerals like rutile, ilmenite, zirconium, tin, phosphates, and some salts. It has been effectively employed in phosphate mineral valorization, specifically to remove silica and carbonates [15,16]. Electrostatic separation processes have been conducted on phosphate minerals from countries such as India, Algeria, Tunisia, and Angola [8].

Electrostatic separation is of economic significance due to the value of phosphate deposits in the arid regions. The results revealed that phosphate is positively charged when interacting with silica, and negatively charged with calcite. One of the few industrial applications of electrostatic separators was at the Pierce plant in Florida, where phosphate concentrate with a P_2O_5 content of 32.9% was recovered and further concentrated to 35.3% P_2O_5 [29].

The electrostatic enrichment tests were conducted at the University of Tafila's Technical Metals Materials Processing Laboratory, using a Carpco-type electrostatic separator. The samples were first vacuum dried at 100 °C before being fed into the separator via a vibratory feeder. For each test, 100 g of a representative sample with a particle size of (-1 + 0.125 mm) was processed under a constant separating voltage of 32 kV, with charger rotation speeds of 25, 50, 75, 100, and 125 r/min, and a 10 cm electrode distance.

3. Results and Discussion

3.1. X-ray fluorescence granulo-chemical analysis

The fractions resulting from the granulometric analysis by dry sieving of the curve grid samples were analyzed using X-Ray Fluorescence (XRF), with the results summarized in Table 1. The chemical analysis reveals that the primary elements in the minerals are P_2O_5, CaO, MgO, and SiO_2. The P_2O_5 contents in the particle size fractions (-1+0.5 mm), (-0.5+0.25 mm), and (-0.25+0.125 mm) are 24.38%, 26.82%, and 23.26%, respectively. The MgO contents in these fractions are 3.07%, 2.88%, and 3.41%, respectively. The chemical analysis results (Table 1, Figure 3) indicate that the black phosphate content in Djebel Onk increases gradually from 0.063 to 0.50 mm, while the MgO content decreases to 2.88% (Figure 3).

3.2. X-ray diffraction mineralogical analysis

X-Ray Diffraction (XRD) is a crucial method for the mineralogical characterization of materials. The results of the XRD analysis are presented in Figure 4, which displays a diffraction pattern with significant peaks corresponding to the minerals fluorapatite, hydroxylapatite, dolomite, quartz, and calcite.

The analysis identifies fluorapatite ($Ca_5(PO_4)_3F$) and hydroxylapatite ($Ca_5(PO_4)_3(OH)$) as the dominant phosphate phases. Additionally, carbonated gangue minerals such as dolomite ($CaMg(CO_3)_2$), calcite ($CaCO_3$), and minor silicates like quartz (SiO_2) are also present. The discovery of yttrium oxide (Y_2O_3) suggests a significant presence of monazite, a rare earth mineral, in these tailings, which strengthens the potential for their revaluation.

3.3. Scanning electron microscope

Scanning Electron Microscopy (SEM) combined with energy-dispersive X-Ray Spectroscopy (EDS) was used to analyze the black phosphate tailings. This approach facilitated the identification of key mineralogical phases including phosphate minerals (pellet and coprolite), dolomite, and quartz. The chemical content was also determined, covering elements like P, Si, Mg, Al, Na, F, C, O, S, and Ca. Figures 5 and 6 show how the SEM-EDS analysis delivers both qualitative and semi-quantitative chemical data, allowing for a detailed characterization of the samples. Figures 5 and 6 illustrate how the SEM-EDS analysis offers both qualitative and semi-quantitative chemical data, aiding in the thorough characterization of the samples.

Table 1. Chemical composition of different particle size fractions of black phosphate from Djebel Onk, as determined by XRF

Size fractions (mm)	Weight (g)	P_2O_5	MgO	CaO	SiO_2	SO_3	K_2O	Fe_2O_3	TiO_2	LOI	CaO/P_2O_5
Global	100	20.04	4.48	59.74	5.84	3.23	0.39	0.92	0.07	0.90	2.98
>4	106.75	17.24	5.71	58.85	8.77	1.85	0.49	1.04	0.10	2.93	3.41
-4+2	36.64	18.91	5.48	60.48	7.11	2.02	0.43	0.93	0.08	1.38	3.19
-2+1	19.50	19.12	4.73	59.92	6.53	2.72	0.37	0.95	0.08	0.70	3.13
-1+0,5	79.32	24.38	3.07	60.30	3.55	2.97	0.31	0.78	0.08	0.44	2.47
-0.5+0,25	57.20	26.82	2.88	60.08	2.34	2.33	0.29	0.67	0.07	1.06	2.20
-0.25+0,125	10.78	23.46	3.41	59.43	1.86	4.67	0.22	0.69	0.08	1.84	2.53
-0.125+0,08	3.90	12.39	4.68	55.18	6.98	9.87	0.44	1.22	0.09	0.18	4.45
-0.08+0,063	18.88	12.08	4.99	53.99	8.37	9.30	0.63	1.70	0.10	0.33	4.46
<0.063	167.00	11.96	6.08	50.21	13.02	8.42	0.84	2.11	0.12	1.60	4.19

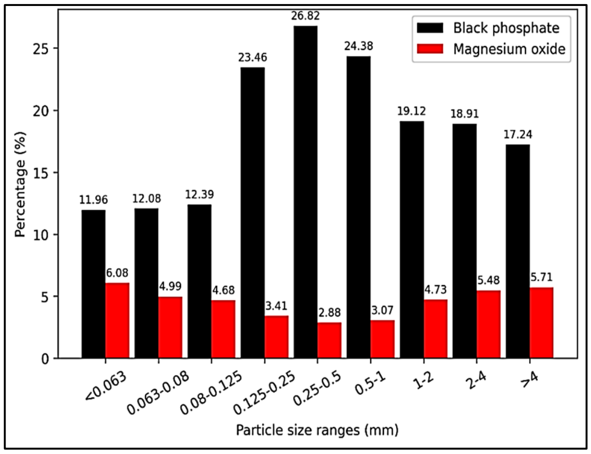

Figure 3. Variation in black phosphate content and MgO concentration across different particle size fractions of Djebel Onk black phosphate.

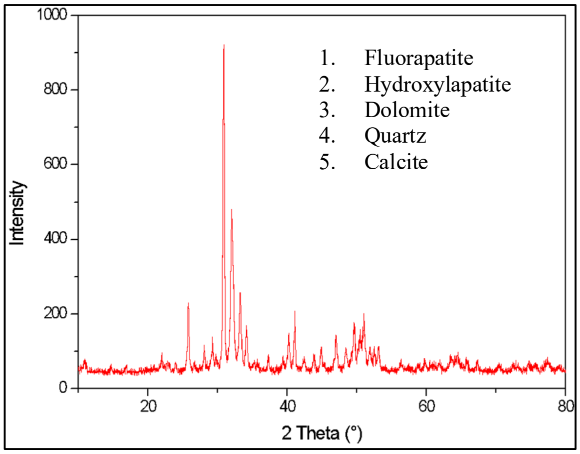

Figure 4. X-Ray Diffraction (XRD) pattern of black phosphate tailings

3.4. Calcination of black phosphate tailings

The calcination tests conducted on the tailings (-1+0.125 mm) demonstrated the evolution of key minerals as a function of temperature and time. The optimal calcination conditions were determined to be 1050 °C for 60 minutes, resulting in a composition of 30.91% P_2O_5, 1.26% MgO, and 1.15% CO_2, with a recovery rate of 91.77% (Table 3).

Chemical analysis, as illustrated in Figure 7, reveals that the P_2O_5 content increases significantly beyond a calcination temperature of 850 °C. In contrast, the percentages of CO_2 and MgO decrease under these conditions. This decrease is attributed to the thermal decomposition of dolomitic and calcitic carbonates, which release CO_2 and transform into CaO and MgO.

The data underscores the significant impact of temperature and time on the contents of P_2O_5, MgO, and CO_2 in the calcined products (refer to Figure 7 and Table 2). Specifically, increasing both temperature and time enhances the yields of phosphates and decomposed carbonates. For a calcination time of 30 minutes, the P_2O_5 content reaches 29.20% at 850 °C, 29.82% at 950 °C, and 30.16% at 1050 °C. When the calcination duration is extended to 60 minutes, the P_2O_5 content increases to 29.69% at 850 °C, 30.07% at 950 °C, and 30.91% at 1050 °C.

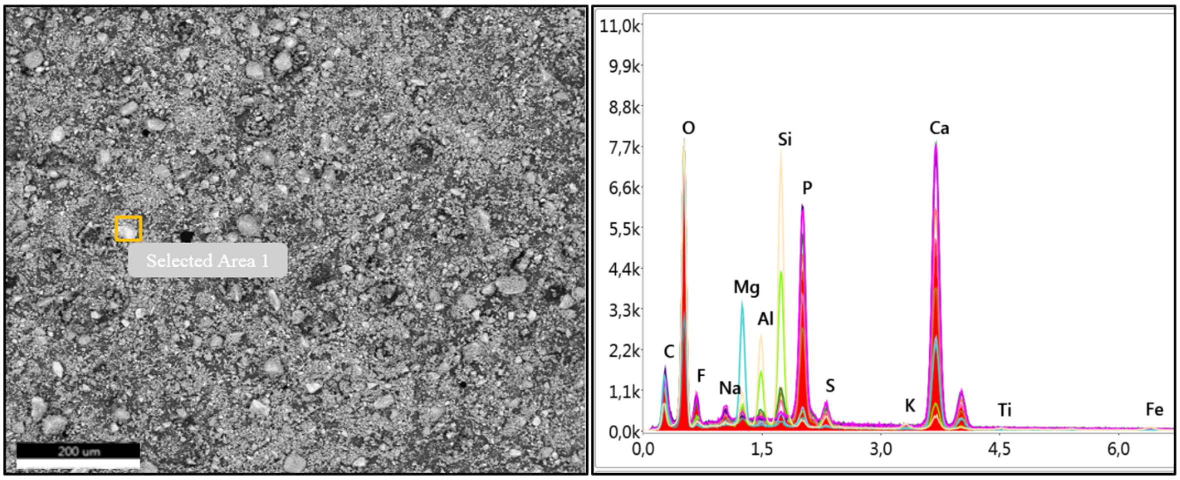

Figure 5. SEM Micrographs and EDX analysis of black phosphate tailings

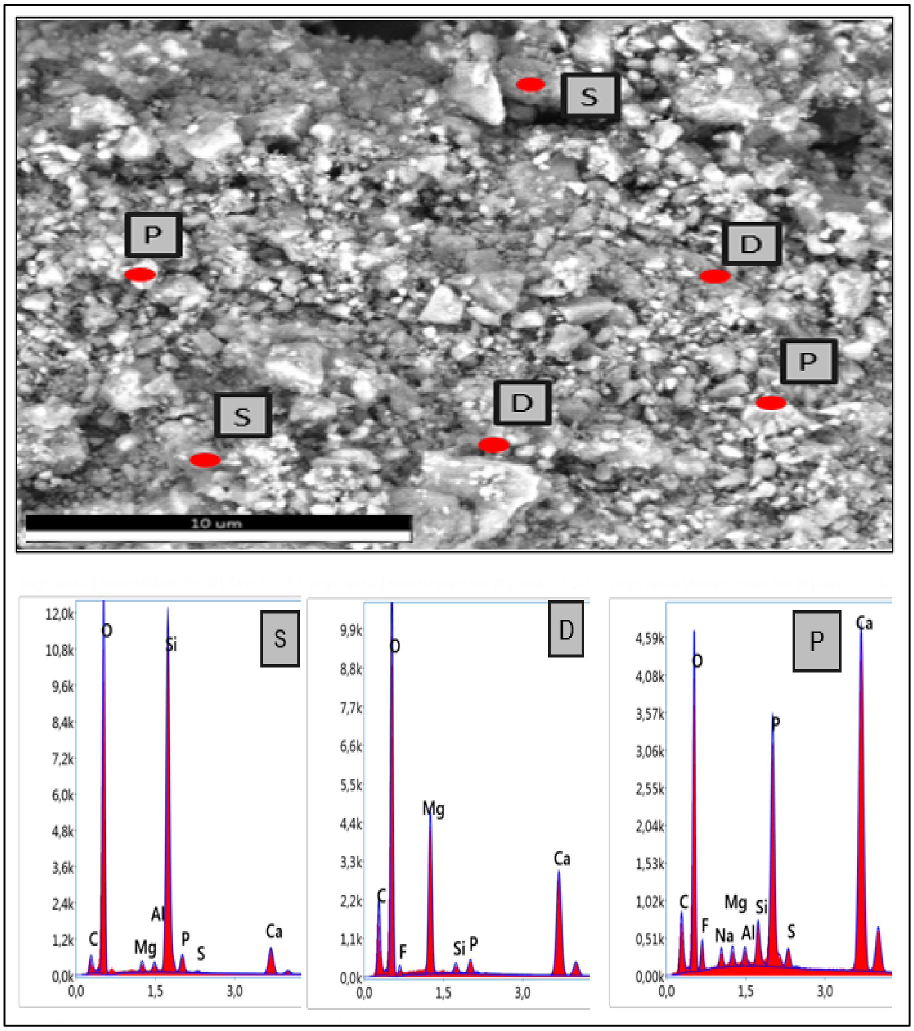

Figure 6. SEM Micrographs and EDX Analysis of selected areas of black phosphate tailings: D – Dolomite; S – Silica; P - Phosphate

Table 2. Effect of calcination temperature and time on the composition of tailings.

Temperature (°c)	Fractions (mm)	Time (min)	P_2O_5 (%)	MgO (%)	CaO (%)	CO_2 (%)	Fe_2O_3 (%)	Na_2O (%)	K_2O (%)	Cd (ppm)	Zn (ppm)	Pb (ppm)	LOI
850	-1+0.125	30	29.20	2.13	47.06	1.51	0.62	0.90	0.006	16.75	110	60.00	13.90
850	-1+0.125	60	29.69	1.94	48.11	1.18	0.64	0.86	0.008	16.75	110	60.50	14.00
950	-1+0.125	30	29.82	1.55	47.18	1.13	0.68	0.93	0.008	15.25	110	69.75	14.15
950	-1+0.125	60	30.07	1.47	48.72	1.05	0.69	0.93	0.006	15.25	110	70.00	14.58
1050	-1+0.125	30	30.16	1.43	48.89	1.26	0.74	0. 85	0.008	15	110	77.75	14.85
1050	-1+0.125	60	30.91	1.26	49.55	1.15	0.70	0.86	0.010	15	110	77.75	15.23

Table 3. Effect of temperature and time on phosphate recovery from tailings.

Temperature (°C)	Fractions (mm)	Time (min)	Feed (g)	Weight (g)	P_2O_5 (%)	Recovery (%)
850	-1 +0.125	30	4	3.10	29.20	89.60
850	-1 +0.125	60	4	3.09	29.69	90.79
950	-1 +0.125	30	4	3.09	29.82	91.19
950	-1 +0.125	60	4	3.07	30.07	91.36
1050	-1 +0.125	30	4	3.05	30.16	91.40
1050	-1 +0.125	60	4	3.00	30.91	91.77

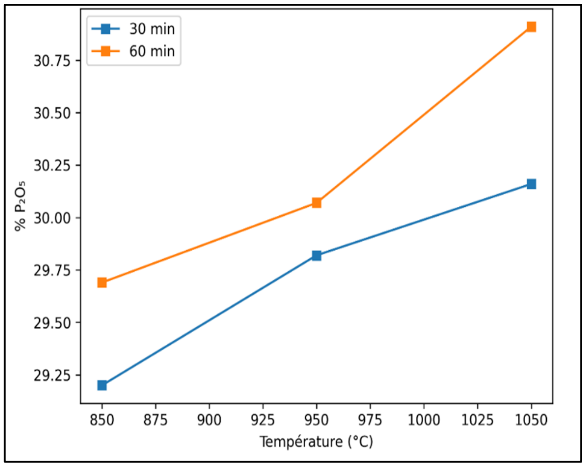

Figure 7. The percentage of P_2O_5 as a function of temperature and time

3.5. Electrostatic separation of black phosphate tailings

The electrostatic separation tests on the -1+0.125 mm tailings demonstrated the impact of roll speed on the separation efficiency. The optimal parameters were identified as a roll speed of 75 r/min and an electric voltage of 32 kV. Under these conditions, the phosphate content achieved was 30.03%, with a recovery rate of 89.70% (see Table 5). These results highlight the effectiveness of electrostatic separation in enriching black phosphate tailings.

Chemical analysis, as shown in Figure 8, reveals that the P_2O_5 content increases with the roll speed up to 75 r/min, beyond which it begins to decrease. Conversely, the MgO content decreases at 75 r/min but increases at higher speeds. This suggests a significant influence of roll speed on the P_2O_5 and MgO contents in the separated products (refer to Figure 8 and Table 4). Specifically, the P_2O_5 content is 27.68% at 25 r/min, 29.16% at 50 r/min, 30.03% at 75 r/min, 28.34% at 100 r/min, and 28.02% at 125 r/min. Meanwhile, the MgO content is 1.56% at 25 r/min, 1.33% at 50 r/min, 1.29% at 75 r/min, 1.40% at 100 r/min, and 1.52% at 125 r/min.

Table 4. Effect of roll speed on the composition of separated products

Tension (KV)	Vitesse (r/min)	Fractions (mm)	P_2O_5 (%)	MgO (%)	CaO (%)	CO_2 (%)	CaO / P_2O_5
32	25	-1+0.125	27.68	1.56	44.28	10.14	1.60
32	50	-1+0.125	29.16	1.33	45.84	9.56	1.57
32	75	-1+0.125	30.03	1.29	45.34	9.72	1.51
32	100	-1+0.125	28.34	1.40	43.64	9.46	1.54
32	125	-1+0.125	28.02	1.52	44.24	9.30	1.58

Table 5. Results of electrostatic separation on phosphate recovery

Tension (KV)	Vitesse (r/min)	Fractions (mm)	P_2O_5 (%)	Weight (g)	Recovery (%)
32	25	-1+0.125	27.68	57.66	63.18
32	50	-1+0.125	29.16	65.61	75.73
32	75	-1+0.125	30.03	75.45	89.70
32	100	-1+0.125	28.34	67.71	75.96
32	125	-1+0.125	28.02	61.97	61.38

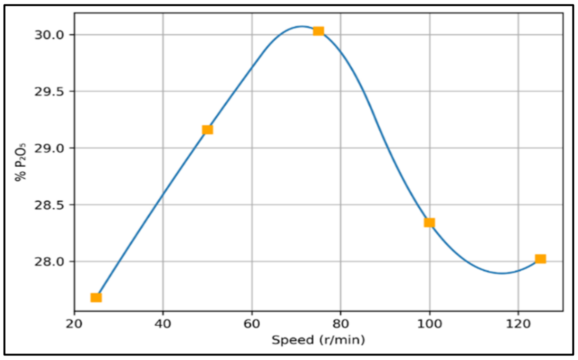

Figure 8. The percentage of P_2O_5 as a function of roll speed

The calcination and electrostatic separation techniques used in this study offer various advantages over other processes such as gravity separation, flotation, and leaching, which often require large amounts of water and chemical reagents, which can generate toxic pollution of water and mine tailings and the environment. On the other hand, calcination and electrostatic separation operate as dry processes, making them more suitable for the arid regions. In addition, electrostatic separation and calcination have been shown to achieve significant recoveries of more than 85% and 90% P_2O_5, respectively, with less environmental risks, while the Djebel Onk phosphate mining complex which uses gravity separation, which offers only a recovery of less than 70% P_2O_5. However, reducing the use of chemicals and water consumption in order to preserve the environmental footprint. This is why global efforts and commitment of mining companies are in favor of integrated management of mine tailings and sustainable development [5,20].

The technical and economic feasibility of applying calcination and electrostatic separation on an industrial scale must be taken into account due to the high investment costs and significant energy requirements, particularly calcination. Previous studies have shown that the energy costs of calcination can be high [13], although these can be reduced by producing high-purity phosphate concentrates, which could generate a significant market value. On the other hand, electrostatic separation offers an alternative to dry processing, saving an energy resource in water, especially for the case of the semi-arid mining region of Jebel Onk. To this end, the applicability of the different processes for enriching phosphate ores must be the subject of a thorough economic study, particularly with regard to the price of energy and the availability of human and material resources as well as the cost price per ton treated.

4. Conclusions

Mining tailings present significant environmental challenges and contribute to an economic loss for the Phosphate Mining Society (SOMIPHOS). This research aims to tackle these challenges by developing efficient treatment techniques for black phosphate tailings, taking into account factors such as the mineral composition, phosphate content, granulometric distribution, and the semi-arid climate of the region.

In order to meet these objectives, black phosphate tailings from the Djebel Onk complex were subjected to two treatment techniques: electrostatic separation and calcination. The study assessed the effectiveness of these approaches in valorizing the tailings, with a focus on recovering phosphate resources and minimizing undesired components.

The study results revealed that both calcination and electrostatic separation present effective solutions for recovering valuable resources from phosphate tailings. Calcination at 1050°C for 60 minutes was identified as the optimal condition, yielding a P_2O_5 content of 30.91% with a phosphate recovery rate of 91% and reducing the MgO content to less than 1.26%. On the other hand, electrostatic separation, optimized at 75 r/min and 32 kV, achieved an 89.70% recovery rate, producing a P_2O_5 content of 30.03% and lowering the MgO content to 1.29%.

These significant results highlight the potential of calcination and electrostatic separation as both effective and sustainable techniques for the valorization of phosphate tailings. These methods enhance the resource recovery and contribute to sustainable development, providing practical solutions for the efficient management of mining by-products.

References

[1]. Moukannaa, S., Loutou, M., Benzaazoua, M., Vitola, L., Alami, J., & Hakkou, R. (2018). Recycling of phosphate mine tailings for the production of geopolymers. *Journal of Cleaner Production*, *185*, 891–903.

[2]. Corchado-Albelo, J. L., & Alagha, L. (2023). Studies on the enrichment feasibility of rare earth-bearing minerals in mine tailings. *Minerals*, *13*(*3*), 301.

[3]. Alsafasfeh, A., Alagha, L., Alzidaneen, A.,

& Nadendla, V. S. S. (2022). Optimization of flotation efficiency of phosphate minerals in mine tailings using polymeric depressants: Experiments and machine learning. *Physicochemical Problems of Mineral Processing*, *58*(4), 150477.

[4]. Birken, I., Bertucci, M., Chappelin, J., & Jorda, E. (2016). Quantification of Impurities, Including Carbonates Speciation for Phosphates Beneficiation by Flotation. *Procedia Engineering*, *138*, 72–84.

[5]. Alsafasfeh, A., Alagha, L., & Al-Hanaktah, A. (2024). The Effect of Methyl Isobutyl Carbinol "MIBC" on the Froth Stability and Flotation Performance of Low-Grade Phosphate Ore. *Mining, Metallurgy and Exploration*, *41*(1), 353–361.

[6]. Abouzeid, A. Z. M. (2008). Physical and thermal treatment of phosphate ores — An overview. *International Journal of Mineral Processing*, *85*(4), 59–84.

[7]. Alsafasfeh, A., Khodakarami, M., Alagha, L., Moats, M., & Molatlhegi, O. (2018). Selective depression of silicates in phosphate flotation using polyacrylamide-grafted nanoparticles. *Minerals Engineering*, *127*, 198–207.

[8]. Bittner, J. D., Gasiorowski, S. A., Hrach, F. J., & Guicherd, H. (2015). *ScienceDirect Electrostatic beneficiation of phosphate ores: Review of past work and discussion of an improved separation system*.

[9]. Zafar, Z. I., Anwar, M. M., & Pritchard, D. W. (1995). Optimization of thermal beneficiation of a low grade dolomitic phosphate rock. *International Journal of Mineral Processing*, *43*(1–2), 123–131.

[10]. Papalas, T., Antzaras, A. N., & Lemonidou, A. A. (2021). Magnesite-derived MgO promoted with molten salts and limestone as highly-efficient CO2 sorbent. *Journal of CO2 Utilization*, *53*, 101725.

[11]. Bahmani, H., Mostafaei, H., Ghiassi, B., Mostofinejad, D., & Wu, C. (2023). A comparative study of calcium hydroxide, calcium oxide, calcined dolomite, and metasilicate as activators for slag-based HPC. *Structures*, *58*, 105653.

[12]. Sajid, M., Bary, G., Asim, M., Ahmad, R., Irfan Ahamad, M., Alotaibi, H., Rehman, A., Khan, I., & Guoliang, Y. (2022). Synoptic view on P ore beneficiation techniques. *Alexandria Engineering Journal*, *61*(4), 3069–3092.

[13]. Guo, F., & Li, J. (2010). Separation strategies for Jordanian phosphate rock with siliceous and calcareous gangues. *International Journal of Mineral Processing*, *97*(1–4), 74–78.

[14]. Ruan, Y., He, D., & Chi, R. (2019). Review on beneficiation techniques and reagents used for phosphate ores. *Minerals*, 9(*4*), 253.

[15]. Derrardjia, N., Nettour, D., Chettibi, M., Chaib, R., Zeghloul, T., Dascalescu, L., & Aouimeur, D. (2024). Study of the feasibility of valorizing phosphate ore by electrostatic separation. *Technology Audit and Production Reserves*, *2*(3(76)), 20–26.

[16]. Anawati, J., & Azimi, G. (2020). Recovery and separation of phosphorus as dicalcium phosphate dihydrate for fertilizer and livestock feed additive production from a low-grade phosphate ore. *RSC Advances*, *10*(63), 38640–38653.

[17]. Dascalescu, L., Zeghloul, T., & Iuga, A. (2016). Electrostatic Separation of Metals and Plastics From Waste Electrical and Electronic Equipment. *WEEE Recycling: Research, Development, and Policies*, 75–106.

[18]. Safhi, A. el M., Amar, H., El Berdai, Y., El Ghorfi, M., Taha, Y., Hakkou, R., Al-Dahhan, M., & Benzaazoua, M. (2022). Characterizations and potential recovery pathways of phosphate mines waste rocks. *Journal of Cleaner Production*, *374*, 134034.

[19]. Zafar Iqbal Zafar, Anwar, M. M., & Pritchard, D. W. (1996). Innovations in beneficiation technology for low grade phosphate rocks. *Nutrient Cycling in Agroecosystems 46*(*2*), 135–151.

[20]. Sobhy, A., & Tao, D. (2014). Innovative RTS Technology for Dry Beneficiation of Phosphate. *Procedia Engineering*, *83*, 111–121.

[21]. Mezghache, H. , Toubal, A. , & Bouima, T. (1980). Typology of phosphate ores in deposits of the Djebel Onk mining basin (eastern Algeria). *Phosphorus Research Bulletin*, *15*, 5–20.

[22]. Kechiched, R., Laouar, R., Bruguier, O., Kocsis, L., Salmi-Laouar, S., Bosch, D., & Larit, H. (2020). Comprehensive REE+ Y and sensitive redox trace elements of Algerian phosphorites (Tébessa, eastern Algeria): A geochemical study and depositional environments tracking. *Journal of Geochemical Exploration*, *208*, 106396.

[23]. Alsafasfeh, A., & Alagha, L. (2017). Recovery of phosphate minerals from plant tailings using direct froth flotation. *Minerals*, *7*(8).

[24]. El Ouardi, E. M., Zeroual, A., Khallouq, K., Darfi, S., & Jedaa, A. (2020). Impact of washing

followed by calcination on the quality of bouchane phosphate of Morocco. *International Journal of Design and Nature and Ecodynamics*, *15*(4), 555–563.

[25]. Cao, W., Yi, W., Peng, J., Li, J., & Yin, S. (2022). Recycling of phosphogypsum to prepare gypsum plaster: Effect of calcination temperature. *Journal of Building Engineering*, *45*, 103511.

[26]. Han, B., Zhao, L., Wang, F., Xu, L., Yu, H., Cui, Y., Zhang, J., & Shi, W. (2020). Effect of Calcination Temperature on the Performance of the Ni@SiO2Catalyst in Methane Dry Reforming. *Industrial and Engineering Chemistry Research*, *59*(30), 13370–13379.

[27]. Han, R., Wang, Y., Xing, S., Pang, C., Hao, Y., Song, C., & Liu, Q. (2022). Progress in reducing calcination reaction temperature of Calcium-Looping CO2 capture technology: A critical review. *Chemical Engineering Journal*, *450*, 137952.

[28]. Kim, J. Y., Ellis, N., Lim, C. J., & Grace, J. R. (2020). Effect of calcination/carbonation and oxidation/reduction on attrition of binary solid species in sorption-enhanced chemical looping reforming. *Fuel*, *271*, 117665.

[29]. Abouzeid, A. (2007). Upgrading of phosphate ores-a review. *Powder Handling and Processing*, *19*(*2*), 92.

استفاده مجدد پایدار از باطله های معدن فسفات سیاه الجزایر برای بازیابی P_2O_5

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چکیده:

منطقه جبل اونک الجزایر با نگرانی زیست محیطی قابل توجهی در ارتباط با زباله های معدن فسفات مواجه است. اگرچه این پسماندهای معدنی حاوی مقادیر نسبتاً کمی از مواد معدنی با ارزش هستند، اما همچنان تا ۲۵٪ P_2O_5 در محدوده اندازه ذرات ۰.۲۵-۱ میلی متر (-۱–+۰.۲۵) دارند که پتانسیل بازیافت و استفاده مجدد را نشان می دهد. این تحقیق بر اساس منطقه Bir El Ater، روش‌های بازیابی مواد معدنی غنی از فسفات و بهینه‌سازی استفاده مجدد از آنها را بررسی می‌کند. دو روش مورد بررسی قرار گرفت: کلسینه کردن، عملیات حرارتی تغییر دهنده شیمی معدنی، و جداسازی الکترواستاتیک، که از خواص الکتریکی برای جداسازی مواد معدنی استفاده می‌کند. باطله‌های فسفات سیاه جمع‌آوری‌شده از شبکه‌های منحنی پردازش مرطوب با استفاده از میکروسکوپ الکترونی روبشی (SEM)، پراش پرتو ایکس (XRD) و فلورسانس اشعه ایکس (XRF) برای بررسی خواص کانی‌شناسی و شیمیایی آن‌ها مورد تجزیه و تحلیل دقیق قرار گرفتند. نتایج بهبود قابل توجهی را در غلظت P_2O_5 نشان داد، با جداسازی الکترواستاتیکی به محتوای ۳۰.۰۳٪ و نرخ بازیابی ۸۹٪، در حالی که کلسیناسیون محتوای ۳۰.۹۱٪ با نرخ بازیابی ۹۱٪ به دست آورد. این نتایج اثربخشی هر دو روش را در بازیابی فسفات از باطله‌های معدنی، کمک به مدیریت بهتر پسماند، استفاده کارآمدتر از منابع و کاهش ردپای محیطی نشان می‌دهد. آنها همچنین مسیرهای بازیابی پایدار را پیشنهاد می‌کنند، به ویژه برای مناطقی که با کمبود آب مواجه هستند، جایی که شناورسازی غیرعملی است. با توانایی دستیابی به نرخ بازیابی بالا بدون ورودی های شیمیایی، کلسینه کردن و جداسازی الکترواستاتیکی به عنوان گزینه های سازگار با محیط زیست برای بهره مندی جهانی از فسفات برجسته می شوند.

کلمات کلیدی: بازیابی فسفات، کلسیناسیون، جداسازی الکترواستاتیک.