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STUDY OF THE FEASIBILITY OF VALORIZING PHOSPHATE ORE BY ELECTROSTATIC SEPARATION

The object of this research is the phosphate serves, as a fundamental and crucial raw material with diverse applications, primarily utilized in producing phosphoric acid and fertilizers. However, dolomitic impurities within the ore can greatly impede its effectiveness. Therefore, it is essential to minimize these impurities to the lowest feasible levels to mitigate their adverse effects. This ensures optimal performance and quality in various industries reliant on phosphate, promoting efficiency and sustainability in the production process. Through a comprehensive assessment, it becomes feasible to gauge the enrichment potential and propose viable methods to realize it. Among these methods, flotation stands out as one of the most effective for enhancing phosphate ore, despite its inherent drawbacks of costliness and environmental impact stemming from chemical reagents.

This study endeavors to investigate the feasibility of employing electrostatic separation as an alternative method for enriching phosphate ore sourced from the Tebessa region in Algeria. Such exploration aims to offer insights into potentially more sustainable and economically viable approaches to ore enrichment in the region of Bir Elater Wilaya of Tebessa. Tests were carried out using different types of electrostatic separators at the Angouleme site of the PPRIME Institute: a multifunctional metal-belt-type separator, a free-fall plate-electrodes-type separator and an electrostatic separator with coaxial wire – cylinder electrode system. The experimental findings demonstrate significant promise, indicating that electrostatic separation enhanced the P_2O_5 content from 25 % to 29 % in an untreated phosphate ore sample. Simultaneously, it efficiently eliminated 82.80 % of MgO, achieving a P_2O_5 recovery rate more than 80 % and a yield of 70 %. Consequently, employing this method proves effective in reducing the MgO content of the ore to below than 1 %, aligning with industrial standards for commercial phosphate products. This underscores the viability of electrostatic separation as a viable and efficient technique in phosphate ore processing, offering substantial improvements in both quality and yield.

Keywords: *electrostatic separation, triboelectric charge, phosphate ore, valorization, enrichment, magnesium carbonate.*

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1. Introduction

Phosphate is a vital non-renewable, non-substitutable, and non-recyclable mineral, extensively used in agricultural applications. The increasing global demand for food production ensures long-term growth in phosphate demand [1–3]. Phosphate rock is never used in its raw state but requires beneficiation to remove the gangue composed of minerals such as quartz, clay, feldspar, mica, calcite, or dolomite. A wide range of techniques and equipment such as froth flotation, calcination, acid leaching, or magnetic separation are employed to enhance low-grade phosphate ores [4, 5]. Froth flotation is the most widely practiced method worldwide. Although recognized as the most effective process for removing silica impurities from phosphate, it is unable to produce high-purity phosphate concentrate and is not efficient in rejecting dolomite from phosphate.

Ores containing carbonate-apatite as the main phosphate minerals and carbonates (calcite and/or dolomite) pose

a challenge in phosphate concentration due to the similar physicochemical properties of the ore constituents [6]. Significant efforts have been made to improve dolomite separation from phosphate using various processes, including specially designed flotation schemes for dolomite removal, washing, selective grinding, dense medium separation, etc. [7–9]. However, none of these processes can reduce dolomite to less than 1 % without a significant loss of phosphate and environmental impact [10–12].

Electrostatic separation techniques use the forces generated by the electric field on small charged or polarized objects to sort the components of granular or powdery mixtures. The efficiency of the sorting mainly depends on the electric charge carried by the granules or the powders to be separated [13, 14]. The first step in electrostatic separation involves imparting an electric charge to the particles, using one or several of the following three physical electrification mechanisms: triboelectric effect, electrostatic induction, and ion bombardment. The separation of charged

particles can then be carried out in facilities with various electrode configurations [15, 16].

In this context, *the aim of this research* was to assess the feasibility of electrostatic separation for removing dolomitic impurities from phosphate, without using water, which is little available in the area, or chemical reagents that are harmful to the environment. As a case study, it is possible to use samples of phosphate ore from the Tebessa region in Algeria.

2. Materials and Methods

2.1. Characteristic data of the deposit

2.1.1. Geographical location of phosphate deposit. The Djebel Onk deposit is located in the northeast of the Algerian Sahara precisely to the east of the Nememcha Mountains, about twenty kilometers from the Algerian-Tunisian border (Fig. 1).

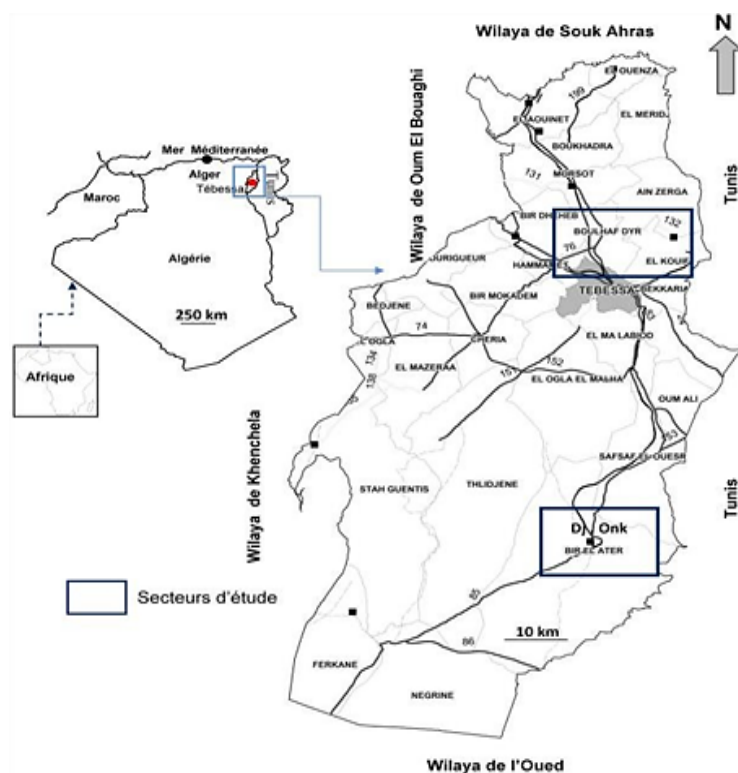


Fig. 1. Geographic map of the wilaya of Tebessa [17]

The relief of the mountainous terrain is very varied. Djebel-Onk culminates at 1338 m at Guern el Kebech, and the land is cut by a wade which is generally dry. The climate is semi-desert, characterized by a continental regime with two very distinct seasons, a cold and harsh winter and a summer where temperatures can exceed 45 °C. Precipitation is scanty with an average of 300 mm/year [17–19].

2.1.2. Petrographic and mineralogical aspect of phosphate ore from Djebel Onk. According to previous studies, the ores of Djebel Onk are grainy, sandy phosphates (pseud-oolites and pellets), often with an organic support. The facies are homogeneous, with fine grains (200 to 300 μm), or heterogeneous, with coarse fine grains (up to 2 to 3 mm). They are powdery to well lithified, and the cement can be clayey, calcitic, or dolomitic. Apart from the phosphate grains, the other figured elements are rare (quartz and glauconite grains, mainly) [20–22].

The mineralogical study has shown that phosphate ores are made up of a phosphate material, which contains an endo-gangue and an exo-gangue [23–25]. The endo-gangue is made up of opal, quartz, illite, water, organic matter and accessory elements. It contains Al_2O_3 , Fe_2O_3 , MgO and SiO_2 in very small quantities (0.3 % of the ore on average for each element).

The exo-gangue is made up of three types of constituents: carbonates where there is a predominance of dolomite ($(\text{Mg}_{0.93}, \text{Ca}_{1.07})\cdot(\text{CO}_3)_2$), sulphates with traces of epsomite ($\text{MgSO}_4\cdot 7\text{H}_2\text{O}$) and silicates, represented by free silica, such as quartz, opal or amorphous silica, feldspar, heulandite, glauconite and illite [26–28]. It should be noted that the phosphated material, in addition to the endo-gangue, represents 5.3 % of it, which is made up of a carbonated fluorapatite ($(\text{P}_{0.88}\text{C}_{0.12}\text{O}_4)_6\text{Ca}_{10}\text{F}_2$) (90 %) and a sulfo-alkaline fluorinated carbonate – earthy (10 %) sometimes hydrated ($(\text{S}, \text{C}, \text{O}_4)_6(\text{K}, \text{Na}, \text{Mg})\cdot \text{F}_2\text{nH}_2\text{O}$) – 97.7 %.

In all the deposits in the Djebel Onk area, a layer of phosphate dolomites tops the productive phosphate layer [29, 30].

The mineralogical constitution being simple, it is therefore clear that for example a phosphate ore having a relatively high content of MgO can only have an essentially dolomitic exo-gangue and that an ore having a high content of Al_2O_3 , Fe_2O_3 and SiO_2 will have an essentially clayey silicate exo-gangue (Fig. 2).

The determination of the type of gangue that will be used to discriminate between types of ores can therefore be carried out on the basis of chemical typology. The mineralogical composition of the Djebel Onk deposit is shown in Table 1.

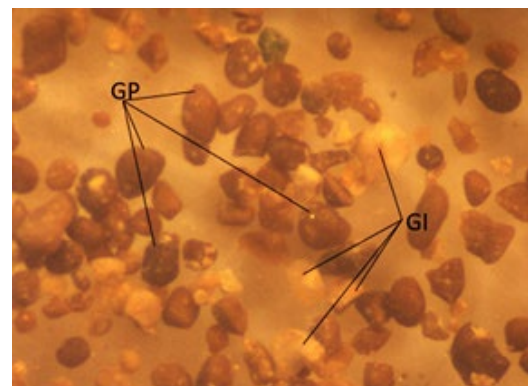


Fig. 2. A sample of phosphate under the optical microscope: GP – grains of phosphate, GI – grains of impurities (limestone dolomite, quartz)

Table 1

The mineralogical composition of the Djebel Onk deposit [18]

Elements	Symbols
Tricalcium phosphate	$\text{Ca}_3(\text{PO}_4)_2$
Calcium carbonate	CaCO_3
Magnesium carbonate	MgCO_3
Dolomite	$\text{CaMg}(\text{CO}_3)_2$
Iron oxide	Fe_2O_3
Gypsum	CaSO_4
Sulfate of soda	Na_2SO_4
Calcium chloride	CaCl_2
Quartz	SiO_2
Alumina	Al_2O_3
Sulfate, fluorine and organic matter	S, F, C

2.2. Sample preparation. The electrostatic separation tests were carried out on samples of raw ore with a particle size less than 1 mm, composed of phosphate minerals as useful material to extract (P_2O_5), quartz (SiO_2) and dolomite ($MgCa(CO_3)$) as impurities to be eliminated. The results of chemical analysis of the phosphate ore by XRF (X-ray fluorescence analyzer) are shown in Table 2.

Several representative samples were taken using a rifle splitter (Fig. 3).

Table 2

XRF chemical analysis of raw material (starting product for all experiments)

Raw material	Analysis 1	Analysis 2	Analysis 3	Average
P_2O_5	24.59	25.55	25.38	25.2
$MgCO_3$	3	3.67	2.4	3
$CaCO_3$	62.77	61.82	62.74	62.44
SiO_2	6.41	6.46	6.78	6.55

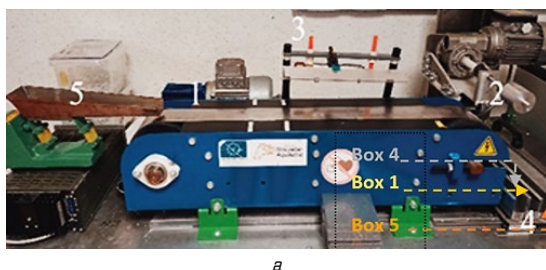


Fig. 3. Rifle divider

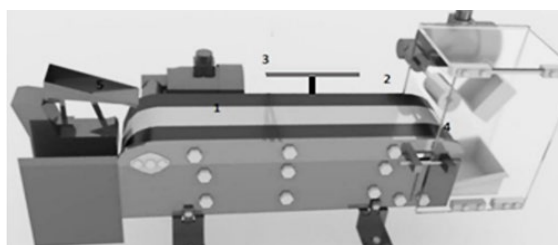
The experiments were carried out under stable relative conditions of temperature ($15.3\text{ °C} \pm 0.8\text{ °C}$) and relative humidity ($70\% \pm 2.6\%$).

2.3. Principle of electrostatic separation. When particles are under the influence of an electric field, depending on their conductivity, they accumulate a charge that directly depends on the maximum charge density that can be achieved on the surface of the particles. These charged particles can be separated by differential attraction or repulsion. Therefore, the first important step in electrostatic separation is to impose an electrostatic charge on the particles.

The tribo-electrification process exploits the difference in the ability of materials to get positively or negatively charged when in contact with each other. In a tribocharging device, the particles become charged through particle-particle contact, particle-wall contact, or both. The contact between different bodies results in the transfer of electric charges from one surface to the other. After this transfer, one of the bodies is positively charged and the other has a negative charge [31–34].



a



b

Fig. 6. Multifunctional electrostatic separator: *a* – photography; *b* – representation of the separator;

1 – metal-belt conveyor connected to the ground; 2 – cylindrical rotating electrode; 3 – active plate electrode; 4 – collection box; 5 – vibro-transporter

2.4. Free-fall plate-electrodes-type electrostatic separator.

A sample of phosphate ore to be separated is first charged by triboelectric effect, for 5 min, in the vibratory-type tribocharging device shown in Fig. 4, provided with a stainless-steel container. A vibro-transporter then introduces the electrically-charged material at a rate of 0.002 g/s into the electric field created by a system of two vertical parallel plane electrodes (Fig. 5), spaced 18 cm apart and connected at $\pm 20\text{ kV}$.

The experiments were carried out under stable relative conditions of temperature ($15.3 \pm 0.7\text{ °C}$) and relative humidity ($74 \pm 1.4\%$).

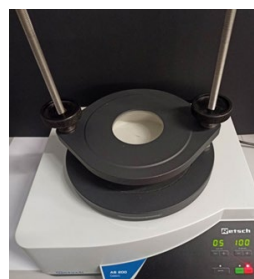


Fig. 4. Retsch AS 200 sieves, used for the study of the triboelectric charging in stainless steel, PLA, HIPS and ABS containers subjected to vibrations of amplitude 2 mm and at a frequency of 50 Hz

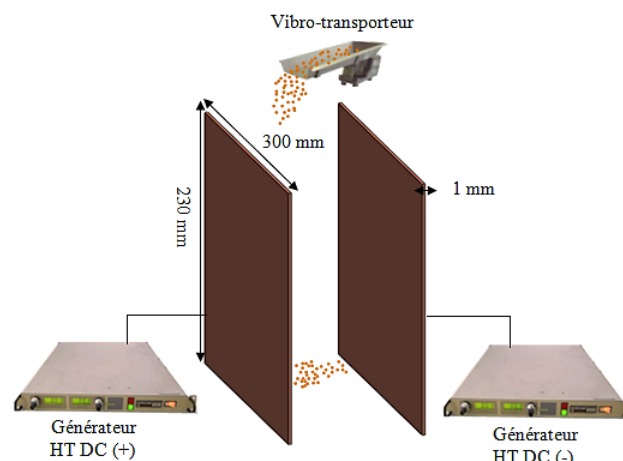


Fig. 5. Electrostatic separator with plate electrodes

2.5. Multifunctional metal-belt-type electrostatic separator.

In this experiment, a preliminary tribo-charging of the material was carried out for 5 min in a copper container, placed on the vibratory device illustrated in Fig. 4. Then the particles transported by the conveyor are attracted unlike polarized and repel those of the same sign during their passage in an electric field generated between the cylindrical electrode 2 connected to the high voltage of +28.5 kV and the metal belt conveyor placed the earth (Fig. 6).

2.6. Electrostatic separator with coaxial wire-cylinder electrode system. The sample is first charged by triboelectric effect, for 10 min using a vibration device equipped with a copper container (Fig. 4). The charged particles are then introduced by a vibro-transporter at a rate of 0.002 g/s into the electric field generated by the coaxial wire-cylinder electrode system of an electrostatic separator, positioned vertically. The device consists of a stainless-steel tube 1000 mm long and 100 mm in diameter, connected to earth. At the center of this cylindrical tube is a metal wire with a diameter of 0.2 mm, connected to a high voltage DC power supply of +13 kV (Fig. 7), the level of which is below the corona discharge inception threshold.

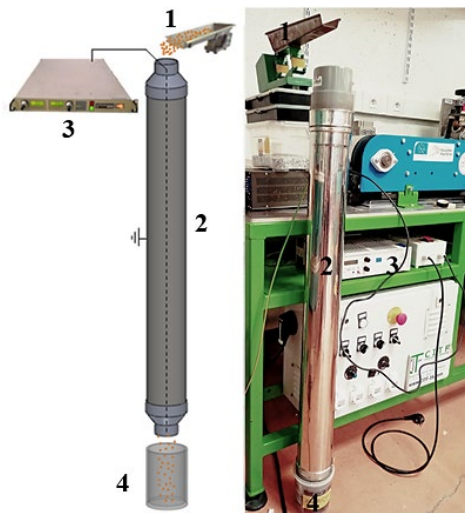


Fig. 7. Electrostatic separator with coaxial wire-cylinder electrode system: 1 – vibro-transporter; 2 – electrode system; 3 – high voltage generator; 4 – recovery tray

When the pre-charged particles enter the separation tube, either they are attracted by electrostatic force to the cylinder wall, or they fall directly under the effect of gravitational force and will be collected at the base of the separator. The particles, which remained stuck on the wall of the cylinder, are recovered by striking, after the elimination of the electric field.

3. Results and Discussions

The mineralurgical processes have the function of carrying out the physical separation of the ore with the aim of producing an enriched fraction containing a major part of the targeted minerals (the concentrate) and a poor fraction consisting almost exclusively of gangue (the rejection). The two parameters for evaluating separation efficiency are recovery and grade. Recovery represents the percentage of the total quantity of a mineral contained in an ore that is recovered in the concentrate. For its part, the grade means the proportion of the mineral in question among the gangue and other minerals present. It is possible to calculate the value of certain operation variables from knowledge of other variables. This is possible by establishing a material balance, which results from the application of the law of conservation of matter in a system.

Material balance:

$$A = C + R. \quad (1)$$

Metal assessment:

$$A(\alpha) = C(\beta) + R(r). \quad (2)$$

The yield (γ) – the yield by weight depending on the grade: From (1) and (2) $\Rightarrow C = A - R$:

$$\begin{aligned} A(\alpha) &= (A - R)(\beta) + R(r) = A\beta - R\beta + Rr \Rightarrow \\ \Rightarrow A(\beta - \alpha) &= R(\beta - r). \end{aligned}$$

– The rejection yield:

$$\gamma_r = \frac{R}{A} \cdot 100 = \frac{(\alpha - \beta)}{(r - \beta)} \cdot 100,$$

$$R = A - C,$$

$$A(\alpha) = C(\beta) + (A - C)r = C(\beta) + Ar - Cr,$$

$$A(\alpha - r) = C(\beta - r);$$

– Concentrated yield:

$$\gamma_c = \frac{C}{A} \cdot 100 = \frac{(\alpha - r)}{(\beta - r)} \cdot 100 \Rightarrow \gamma_A = \gamma_c + \gamma_r = 100 \%,$$

Recovery/Extraction rate (ϵ) – the metal yield depending on the grade:

$$\epsilon_c = \frac{C(\beta)}{A(\alpha)} \cdot 100 = \frac{(\alpha - r)\beta}{(\beta - r)\alpha} \cdot 100 \Rightarrow \epsilon_c = \gamma_c \left(\frac{\beta}{\alpha} \right) 100,$$

$$\epsilon_r = \frac{R(r)}{A(\alpha)} \cdot 100 = \frac{(\alpha - \beta)r}{(r - \beta)\alpha} \cdot 100 \Rightarrow$$

$$\Rightarrow \epsilon_r = \gamma_r \left(\frac{r}{\alpha} \right) 100 \Rightarrow \epsilon_A = \epsilon_c + \epsilon_r = 100 \%,$$

where A , C , R are respectively the weight of the feed, the weight of the concentrate, the weight of the reject; α , β , r are respectively the content of useful «metal» component in the run-of-mine, content of useful «metal» component in the concentrate, content of useful «metal» component in the waste; γ_c , γ_r , γ_i are respectively the yield of the concentrate, the yield of the rejects and that of the intermediate product; ϵ is the recovery or extraction rate of the useful component in a product with the corresponding index.

The results of the experiments carried out with the free fall separator are presented in Table 3. The fraction attracted by the positive electrode (the concentrate) represents 56.4 % of the feed, and contains respectively 66.9 % phosphate material, 41.3 % siliceous impurities and a quantity of dolomite not detectable by the analyzer; its P_2O_5 content reaches 29.91 %.

Three products are obtained by multifunctional electrostatic separator: concentrate, mixed and rejection, its chemical analyzes by XRF presented in Table 4 show that:

- 95.24 % of the phosphate minerals fall into the middle box (Box 1 (concentrate)) with a yield high (87.27 %) and a moderately low grade (27.5 % P_2O_5);
- most of the dolomitic impurities (88.33 % MgO) and a small portion of silica (14.65 % SiO_2) are distributed towards two ends opposite (Box 4 and Box 5);
- however, a part of phosphate was carried with the dolomite towards Box 5.

Table 3

Results of free-fall electrostatic separation of charged samples by triboelectric effect

Product	Weight (g)	Grade (%)				Yield (γ %)	Recovery (ϵ %)			
		P ₂ O ₅	MgO	CaO	SiO ₂		P ₂ O ₅	MgO	CaO	SiO ₂
Feed	5.5	25.2	1.4	34.96	6.55	100	100	100	100	100
Concentrate (electrode +)	3.1	29.91	<LOD	34.5	4.8	56.4	66.94	–	55.66	41.3
Rejection (electrode –)	2.4	18.26	3.2	35.08	8.70	43.6	31.6	100	43.78	57.95

Table 4

Results obtained by multifunctional electrostatic separator

Product	Weight (g)	Grade (%)				Yield (γ %)	Recovery (ϵ %)			
		P ₂ O ₅	MgO	CaO	SiO ₂		P ₂ O ₅	MgO	CaO	SiO ₂
Feed	3.3	25.2	1.4	34.96	6.55	100	100	100	100	100
Box 4 (rejection)	0.2	0.84	15.68	30.75	8.34	6.06	0.2	67.87	5.33	7.7
Box 1 (concentrate)	2.88	27.5	0.18	34.98	6.4	87.27	95.24	11.22	87.32	85.27
Box 5 (mixed)	0.22	15	4.34	35.46	6.9	6.6	3.93	20.46	6.69	6.95

The chemical analysis of the two products obtained by the electrostatic separator with coaxial wire-cylinder electrodes shown in Table 5, shows that this separator very effectively eliminates dolomite (82.80 % MgO) from phosphate ore, with a moderately high yield (70.1 %) and a P₂O₅ grade of 29 %, hence the phosphate extraction rate after separation is 80.75 %.

As research outcomes, it is possible to state that the technique employed holds paramount importance for the ore mineral processing of the Bir Elater deposit ore and has yielded promising results. It has shown an effective removal rate of dolomite (over 82 % MgCO₃) from the phosphate ore and achieved a phosphate extraction rate of 80.75 % post-separation. Consequently, this mining beneficiation technique can be expanded and successfully applied to other deposits with similar mineralogical compositions, such as the Khouribga deposit in Morocco and the phosphate Gafsa basin in southern of Tunisia. To materialize these advancements, let's recommend the implementation of this technique to the stakeholders of the Bir Elater mining operation.

Regarding future prospects, in terms of research, the results are encouraging. A thorough analysis of samples taken from the Djebel Onk ores are conducted using various methods such as granulometry, granulochemistry, optical observation, and X-ray fluorescence analysis to characterize the ore, supplemented by beneficiation tests using electrostatic separation technique. Furthermore, for the case study, there are promising results. However, these results still need to be demonstrated on an industrial scale.

This advancement in research paves the way for new opportunities in the field of mineral processing, offering potentially effective and sustainable solutions for mineral resource exploitation. Through a methodical and innovative approach, let's contribute to the advancement of science and the economic growth of the region.

4. Conclusions

According to this study, electrostatic separation is effective in concentrating phosphate ore originating from a subarid region, while removing a large proportion of dolomite and a small amount of silica. The various models of electrostatic separators used produced similar results with slight variations.

The electrostatic concentrator with coaxial wire-cylinder electrodes made it possible to achieve the best separation of the phosphate ore, from which 80.75 % of the phosphate material (P₂O₅) was recovered while increasing the content from 25 to 29 % (P₂O₅) with a removal of 82.80 % of dolomitic impurities (MgO), moreover, the weight yield of the concentrate exceeds 70 %. Further research with some adjustments can demonstrate that the electrostatic separation process could be adapted to remove silica while increasing the phosphate content of the commercial product, to meet industrial requirements.

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Conflict of interest

The authors declare that they have no conflict of interest concerning this research, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Table 5

Electrostatic separation results in coaxial wire-cylinder electrode system

Product	Weight (g)	Grade (%)				Yield (γ %)	Recovery (ϵ %)			
		P ₂ O ₅	MgO	CaO	SiO ₂		P ₂ O ₅	MgO	CaO	SiO ₂
Feed	5.7	25.2	1.4	34.96	6.55	100	100	100	100	100
Concentrate (non-adherent particles)	4	29.03	0.34	35.65	4	70.1	80.75	17.02	71.48	42.8
Rejection (adhering particles)	1.7	15.32	3.89	32.9	12.5	29.8	18.11	82.80	28.04	56.87

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Data availability

There is no data associated with the manuscript.

Use of artificial intelligence

The authors confirm that artificial intelligence technologies were not utilized in the creation of the current work.

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