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Toward Sustainable Phosphate Mining in Jordan: A Case Study on Eshidiya Mine, Southeast Jordan

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Abstract

Phosphate rock is a strategically critical non-renewable resource, underpinning global food security and numerous industrial sectors. Jordan ranks among the world's leading phosphate producers, with Eshidiya Mine representing one of its most important operations of Jordan Phosphate Company (JPMC). Current beneficiation practices at Eshidiya generate substantial volumes of coarse reject phosphate (>12.5 mm) and fine slime, which are largely stockpiled or disposed of despite containing significant residual phosphate values. This study provides a comprehensive mineralogical, chemical, and beneficiation assessment of these waste streams derived from the A1, A2, and A3 phosphate layers and slime. Representative samples of reject material and slime were subjected to crushing, wet sieving, washing tests, petrographic studies, X-ray fluorescence (XRF), and X-ray diffraction (XRD). The results demonstrate that reject materials from the A1 and A2 layers retain high tricalcium phosphate (TCP) contents (68% - 74%), comparable to saleable concentrate, while A3 rejects respond positively to multistage washing, retain of 57.9%. Slime from the A1 circuit contains approximately 46% TCP, indicating a significant recoverable resource. To facilitate implementation, it is recommended that JPMC adopt a phased integration strategy, beginning with pilot-scale trials for A1-A2 reject reintegration, followed by modular washing units for A3 material and controlled slime blending programs. These findings indicate that reprocessing of reject phosphate and selective utilization of slime can significantly enhance overall phosphate recovery, reduce waste generation, and contribute to extending the operational life of the Eshidiya Mine through conversion of waste streams into secondary resources. Adoption of a circular-economy-based waste valorization strategy is therefore strongly recommended to improve the long-term environmental and economic sustainability of phosphate mining in Jordan.

Keywords

Phosphate Mining, Beneficiation, Mine Waste Valorization, Circular Economy, Sustainability, Jordan

1. Introduction

Phosphate rock is an essential raw material for the production of phosphorus-based fertilizers and a wide range of chemical and industrial products [1]. As global demand for food and fertilizers continues to rise, pressure on high-grade phosphate reserves has intensified, necessitating improved efficiency in resource utilization and waste management [2]-[11]. Jordan is one of the world's major phosphate producers, and the Eshidiya Mine, operated by the Jordan Phosphate Mines Company (JPMC), represents one of the country's largest and highest-quality deposits (**Figure 1**).

Conventional phosphate beneficiation at Eshidiya relies on crushing, screening, washing, and, in selected cases, flotation [11]. These processes generate significant quantities of coarse reject material and fine slime, which have historically been considered waste and disposed as a stockpiles or tailings ponds. Such practices not only result in the loss of potentially valuable phosphate resources, but also create long-term environmental liabilities related to land use, dust generation, and water management [12].

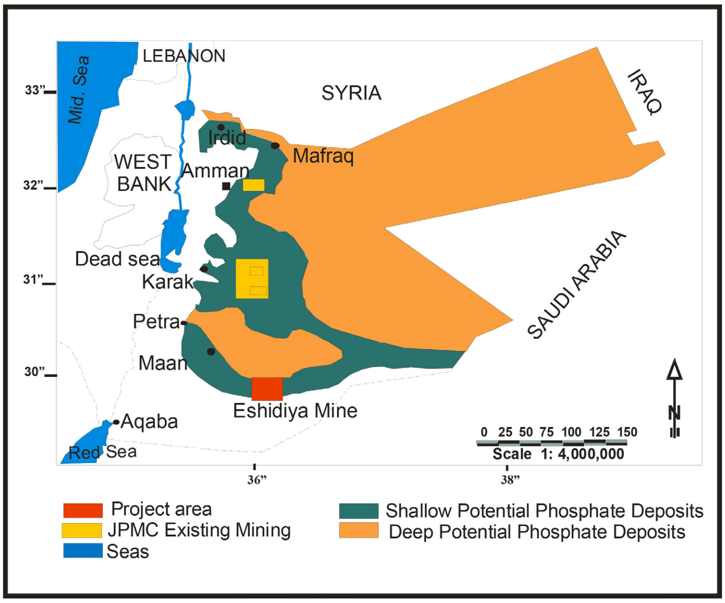


Figure 1. Phosphate location map at Jordan.

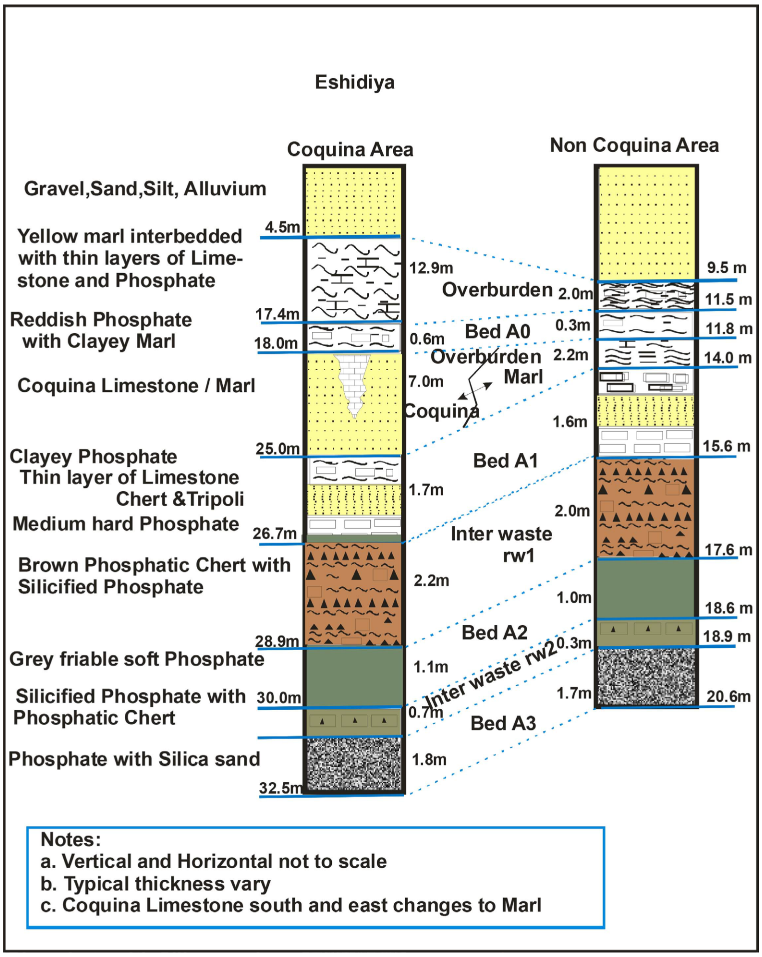
In recent years, sustainable mining and circular economy concepts have emphasized the need to re-evaluate mine waste streams as secondary resources rather than liabilities [12]. Reprocessing of reject materials and utilization of slime have been successfully implemented in several mining sectors worldwide, leading to enhanced resource efficiency and reduced environmental impact. Against this background, the present study aims to 1) characterize the mineralogical and chemical properties of reject phosphate and slime generated at the Eshidiya Mine, 2) evaluate their beneficiation potential using relatively simple and low-cost processing routes, and 3) assess their role in supporting a more sustainable and circular phosphate mining industry in Jordan.

2. Geological and Mining Background

2.1. Geological Setting

Jordanian phosphate deposits are part of the Upper Cretaceous (Campanian-Maastrichtian) sedimentary sequence, which covers approximately 60% of the country [4] [8] [13]-[18].

At Eshidiya Mine, the phosphate occurs in laterally continuous beds subdivided into three principal economic horizons: A1 (Upper), A2 (Middle), and A3 (Lower) [19]. These horizons differ in thickness, grade, and impurity content of P_2O_5 (**Figure 2**).



Notes:
a. Vertical and Horizontal not to scale
b. Typical thickness vary
c. Coquina Limestone south and east changes to Marl

Figure 2. Lithological section of Eshidiya mine.

The A2 layer is generally the highest-grade unit, with TCP values reaching 71% - 74%, and is often marketed after minimal processing. In contrast, the A1 and A3 layers typically require beneficiation to meet commercial specifications. Mineralogically, the phosphate rock is dominated by apatite, primarily carbonate fluorapatite (francolite), accompanied by varying proportions of calcite, quartz, and clay minerals [4] [5].

2.2. Mining and Beneficiation Practices

Eshidiya Mine is operated by using open-pit mining methods. Run-of-mine ore is crushed and screened at 12.5 mm. Oversize material is currently classified as reject, while undersize fractions undergo washing, and for the A3 layer, additional flotation carried out to reduce the silica content. Washing processes generate significant volumes of fine slime, which are pumped to evaporation ponds. These reject and slime streams form the focus of the present investigation as described in **Figure 3**.

3. Materials and Methods

Representative samples of coarse reject phosphate (>12.5 mm) were collected from dedicated stockpiles for the A1, A2, and A3 layers. For each stockpile, five composite samples were created, each consisting of 15 increments (≈2 kg per increment) taken systematically across the stockpile surface to ensure spatial coverage. Slime samples were collected from three different points within the A1 washing circuit pond. All samples were homogenized, quartered, and split for analysis. Replicate assays (n = 3) were performed on head samples for key parameters (TCP, AIR, Cl) to assess their variability.

3.1. Sample Preparation and Beneficiation Tests

Beneficiation tests were designed to reflect practical, low-cost processing options (**Figure 3**). Coarse rejects were jaw-crushed with a gap setting of 10 mm to achieve a target P80 of <4 mm. The crushed material was then subjected to wet sieving, where:

- **A1 Reject:** Simple washing was performed at a water-to-solids ratio of 3:1 (v/w) with 10 minutes of agitation, followed by wet sieving at 2.0, 1.0, and 0.75 mm. No desliming was applied prior to sieving.
- **A2 Reject:** Simple wet sieving was conducted at the same size fractions without a prior washing stage (5 minutes screening time per fraction).
- **A3 Reject:** Multistage washing involved four successive stages, each at a 3:1 water-to-solids ratio with 10 minutes of agitation and scrubbing. After the final stage, the material was wet-screened at 2.0, 1.0, and 0.75 mm.

Preliminary particle-size distribution (PSD) analysis of the rejects indicated that phosphate (francolite) was sufficiently liberated below 4 mm. Qualitative SEM/XRD observation of the −0.75 mm fraction confirmed that fines were enriched in liberated apatite micro-crystals, justifying the selected grind size and the effectiveness of washing for clay removal.

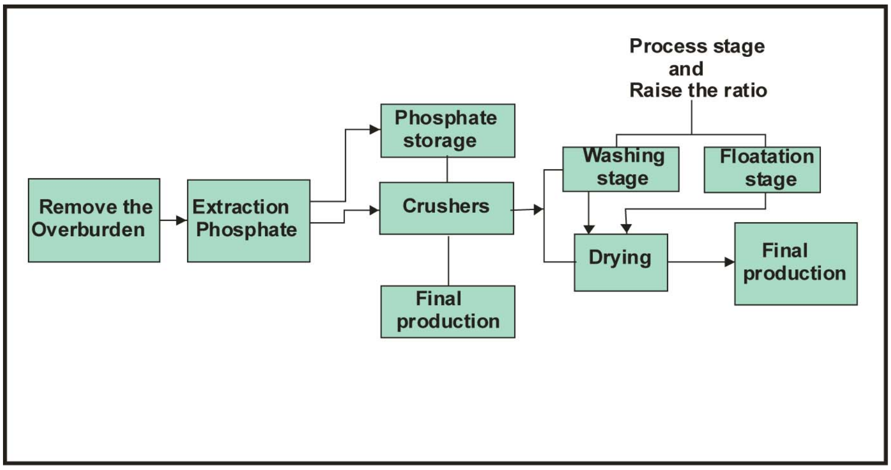


Figure 3. Mineral processing diagram of phospahte at Eshediya mine.

3.2. Chemical and Mineralogical Analysis

Mineralogical characterization was performed using X-ray diffraction (XRD), optical microscopy, and scanning electron microscopy (SEM). The Major oxide composition was determined by X-ray fluorescence (XRF), including P_2O_5, CaO, SiO_2, Al_2O_3, Fe_2O_3, and minor constituents.

All phosphate grades in this study were analytically determined as P_2O_5. Tricalcium phosphate (TCP) values reported throughout the manuscript were calculated using the standard industrial conversion factor TCP (%) = P_2O_5 (%) × 2.186, in accordance with JPMC operational and regional marketing practice. Acid-insoluble residue (AIR) was determined by hydrochloric acid digestion, and chloride content was measured potentiometrically.

4. Results

4.1. Mineralogical Characterization

The Jordanian phosphates are composed mainly of pellets, intraclasts, skeletal fragments, and coated grains, consistent with previous studies on Upper Cretaceous phosphorites in Jordan [5] [18] [19]. Petrographic examination reveals that the phosphate is predominantly of grainstone to pelletal type, interpreted as a reworked product of synsedimentary phosphatized mud deposited in low-energy, organic-rich marine environments [20]-[24]. The processing of washing and transport would concentrate the phosphorite particles "Pellets" generated as phosphorite beds within tectonic troughs in near shore setting due to upwelling [24]. Phosphate rocks are mostly composed of different varieties of apatite. Generally, they include fluorapatite, carbonate-flourapatite (francolite), carbonate hydroxylapatite (dahlite) and chlor-apatite.

The composition of phosphate in the study area is similar to other phosphates in Jordan, with small differences in the amount of the phosphatic particles and silica content. As a rule grains constitute most of the phosphatic part of phosphate layers. The matrix is usually siliceous and locally calcite (sparitic or micritic type). Clay minerals and phosphatic matrices are also present in the groundmass of the rock.

Microscopic observations (**Figure 4(A)**, **Figure 4(B)**) show isotropic yellow–brown phosphate filling skeletal materials (bones and fish teeth) and occurring as microcrystalline aggregates surrounded by quartz and micritic calcite. SEM backscattered electron images confirm the dense microcrystalline nature of the apatite infilling skeletal fragments (**Figure 4(C)**, **Figure 4(D)**).

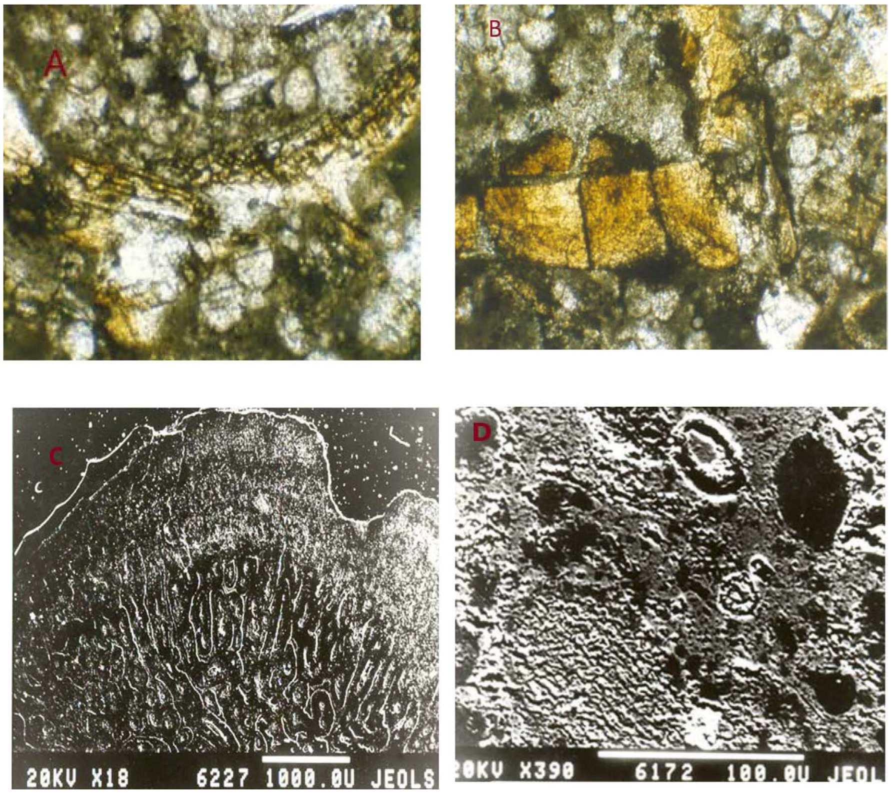


Figure 4. (A) Isotropic phosphate (yellow brown color) filling skeletal materials, surrounded by quartz grains (colorless) and micritic calcite (PPL, ×50); (B) Isotropic phosphate filling fish teeth (yellow brown color), surrounded by quartz grains (colorless) and micritic calcite (PPL, ×50); (C) SEM backscattered electron image of microcrystalline phosphate filling bone fragments (×18); (D) SEM backscattered electron image of microcrystalline phosphate filling microskeletal materials (×390).

X-ray diffraction analysis confirms that the dominant phosphate mineral is carbonate fluorapatite type (francolite), with gangue minerals of quartz and calcite as secondary minerals (**Figure 5**).

4.2. Chemical Characterization of Head Samples

Table 1 summarizes the chemical composition of the unprocessed head samples from the three phosphate layers. The A2 layer exhibits the highest grade, with

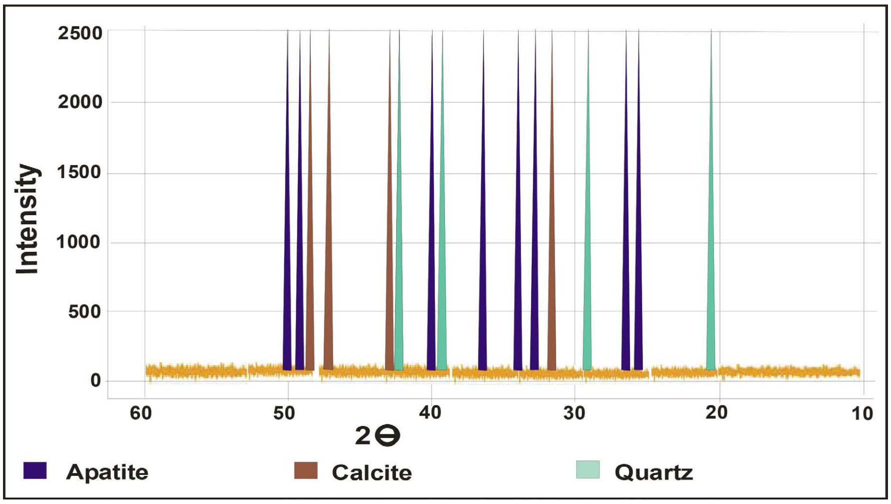


Figure 5. XRD pattern showing apatite (francolite), quartz and calcite as the main mineral composition of study phosphate.

TCP values of approximately 73%, while the A1 and A3 layers show lower TCP contents 55% and 48%, respectively, and higher acid-insoluble residue (AIR) 22.75%, and 22.50%, respectively, reflecting higher siliceous impurity levels. The Cl content varies between 750 and 800 ppm in three layers that indicating similar sedimentary environment condition of phosphate formation (Table 1).

Table 1. Chemical analysis of head samples before processing.

Layer	TCP (%)	P_2O_5 (%)	AIR (%)	Cl (ppm)
A1	55	25	22.75	750
A2	73	33	17.00	800
A3	48	21	22.50	800

4.3. Effect of Processing on Phosphate Quality

After crushing and sieving, reject materials from A1 and A2 exhibited TCP values closely matching those of processed ore, where A1 from plant product reach up to 68.0% (after washing); A2 from plant product reach up to 74.0% (after sieving), whereas A3 as washed reject reach up to 57.9% (Table 2). For A1, the average TCP of rejects was 67.2% (Table 3), and A2 rejects averaged 70.7% TCP (Table 4), whereas A3 rejects responded positively to multi-stage washing, with TCP increasing from 48% in the head sample to an average of 57.9% in the washed reject material (Table 2 and Table 5). Meanwhile, mineral processing effectively reduced chloride and acid-insoluble residue (AIR) content in the A1 and A3 layers, as detailed in Table 2 and shown in Figure 6.

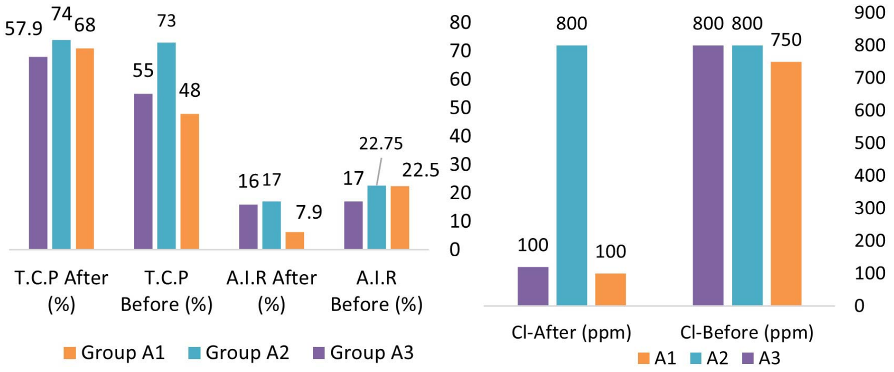
4.4. Wet Sieving Results of Reject Phosphate

Wet sieving of crushed reject material demonstrates that fine fractions are consistently enriched in phosphate. For the A1 reject, TCP values range between

66.2% and 68.1%, with an average of 67.2% as shown in Table 3.

Table 2. Chemical analysis of Key Streams after processing.

Layer	Stream Description	TCP (%)	AIR (%)	Cl (ppm)
A1	Plant Product (After Washing)	68.0	16.00	100
A2	Plant Product (After Sieving)	74.0	17.00	800
A3	**Washed Reject** (This study)	**57.9**	**7.9**	**100**



(a) (b)

Figure 6. Comparison of TCP, AIR, and Cl values for the three phosphate layers before processing (head sample) and after processing. Note: "After Processing" for A3 represents the washed reject stream (this study), not the plant product.

Table 3. Wet sieving results for A1 reject sample.

Sieve size (mm)	TCP (%)	AIR (%)	Cl (ppm)
2.0	66.2	9.57	100
1.0	67.3	6.50	100
0.75	68.1	6.70	100
Average	**67.2**	**7.5**	**100**

Similar trends were observed for the A2 reject material, where TCP values have average of 70.7% after wet sieving as shown in Table 4.

Table 4. Wet sieving results for A2 rejects sample.

Sieve size (mm)	TCP (%)	AIR (%)	Cl (ppm)
2.0	70.3	18.40	100
1.0	70.4	9.52	100
0.75	71.5	6.64	100
Average	**70.7**	**11.5**	**100**

For the A3 layer, multistage washing increased TCP values from 48% in the head sample to an average of 57.9% in the reject material as shown in Table 5.

Table 5. Wet sieving results for A3 reject sample after washing.

Sieve size (mm)	TCP (%)	AIR (%)	Cl (ppm)
2.0	56.5	9.90	100
1.0	58.0	7.02	100
0.75	59.1	6.68	100
Average	**57.9**	**7.9**	**100**

4.5. Slime Characterization

Operationally, the slime corresponds predominantly to the −0.75 mm size fraction generated during the washing circuit. This fine fraction consists mainly of clay-sized particles and liberated apatite micro-crystals, as supported by SEM and XRD observations. The chemical composition of the slime produced from the A1 washing circuit is summarized in Table 6 and Table 7 and illustrated in Figure 7. The slime fraction contains substantial phosphate values, with total phosphate (TCP) ranging from 45.0 to 47.3 wt.% and an average of 46.15 wt.%, indicating that a significant proportion of phosphate is lost to the fine-sized fraction during washing. In addition, the chlorine (Cl) content decreases to 471 ppm in the slime compared with 750 ppm in the head sample. In contrast, the acid-insoluble residue (AIR) increases to 26.7 wt.% relative to 22.75 wt.% in the head sample, reflecting an enrichment of gangue minerals in the fine fraction (Figure 7).

Table 6. Major oxide composition (XRF) of A1 slime sample.

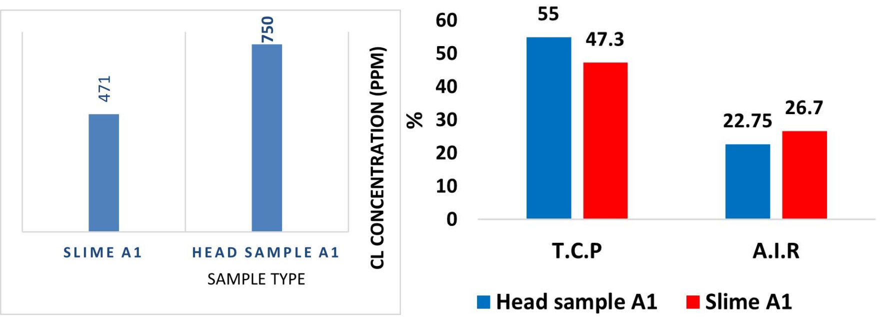
Oxide	Content (%)
CaO	48.34
SiO_2	22.33
P_2O_5	21.64
Fe_2O_3	3.89
Al_2O_3	1.61
Others	<1

Table 7. Summary chemical parameters of A1 slime compared with head sample.

Sample	TCP (%)	AIR (%)	Cl (ppm)
Slime (A1)	47.3	26.7	471
Head sample (A1)	55.0	22.75	750

4.6. Mass Balance and Phosphate Recovery

A simplified mass balance was conducted for the beneficiation tests on reject material. Table 8 presents the mass yield (%) for the product (+0.75 mm fraction), (72.8% for A3 (reject washed; 88.5% for A2 reject and 85.2% for A1 reject), whereas the TCP recovery was 81.1% for A3 (washed reject); 89.4 (%) for A2 reject and 86.1% for A1 reject, relative to the crushed reject feed for each layer. This confirming the resource potential of these waste streams. It should be noticed that the feed of TCP % is the weighted average of the crushed reject before sieving. Product refers to the combined +0.75 mm fractions, whereas slime (−0.75 mm) and moisture losses account for the remaining mass.



(a) (b)

Figure 7. Comparison between TCP, AIR and Cl values of A1 head sample and slime.

Table 8. Mass balance and TCP recovery from reject processing.

Layer	Feed TCP (%)	Product TCP (%)	Mass Yield to Product (%)	TCP Recovery (%)
A1 Reject	66.5	67.2	85.2	86.1
A2 Reject	70.0	70.7	88.5	89.4
A3 Reject (Washed)	52.0	57.9	72.8	81.1

5. Discussion

5.1. Reprocessing Potential of Reject Phosphate

The analytical results demonstrate that coarse reject materials from A1 and A2 are of remarkably high grade, with TCP levels only marginally below those of the saleable product. This suggests that the current practice of rejecting +12.5 mm material is based on historical processing constraints rather than quality considerations. Re-crushing and re-feeding this material into the beneficiation circuit could recover significant phosphate units without substantial additional processing cost.

For A3, the reject material is lower in grade and higher in silica, but multi-stage washing achieved a TCP increase from 48% in the head sample to 57.9% in the washed reject (Table 5), with a corresponding TCP recovery of 81.1% (Table 8). This demonstrates a significant upgrade potential through simple hydraulic methods. Although flotation represents an effective long-term solution for fine slime upgrading, the present study prioritizes low-cost and immediately deployable processing routes that can be integrated into existing JPMC infrastructure with minimal capital investment. Flotation-based upgrading of slime is therefore recommended as a subsequent optimization stage.

The slime sample, though high in acid-insoluble residue, contains ~46% TCP.

This material could be used in several ways: 1) as a filler in phosphate-based products, 2) blended with higher-grade concentrates for specific fertilizer formulations, or 3) pelletized for direct application in agriculture. Successful slime utilization would also mitigate the environmental risks associated with large-scale tailings storage [24] [25].

Integrating reject and slime streams into the production cycle aligns with circular economy principles, which aim to minimize waste and maximize resource efficiency [25]. For Eshidiya, this approach could lead to extend mine life by converting waste into reserve; reduce land disturbance and tailings footprint; lower specific water and energy consumption per ton of phosphate produced and enhance economic resilience by creating value from previously discarded stockpiled. These findings contribute to our understanding of the mechanisms of nanoparticles-based collectors which facilitate the development of more efficient and environmentally friendly phosphorite collectors [8] [25].

Quantitatively, if just 20% of the historically stockpiled reject (estimated at hundreds of thousands of tons) were recovered, it could add several years of production at current rates. This represents a tangible contribution to the sustainable development goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 9 (Industry, Innovation and Infrastructure) [26] [27].

The most common key challenges could include: Processing costs that need additional crushing and handling may increase operational expenses; market acceptance related to blended, or lower-grade products must meet customer specifications; water management by re-processing of slime requires careful water-balance planning and regulatory framework, which is related to Jordanian mining policies that will may need updating to incentivize waste valorization [28].

It can be assumed that for industry and policy in phosphate mining should take into consideration immediate actions. JPMC should conduct a detailed audit of all reject stockpiles and slime ponds to quantify the recoverable resource. The pilot-scale trials should test the re-crushing and re-processing of reject material in the existing plant [28]. Also medium-term strategies through investment in optimized crushing circuits to handle coarse rejects efficiently, develop blending formulations that incorporate slime into saleable products and to enhance water-recycling systems to make slime re-processing sustainable [27]. The Jordanian Ministry of Energy and Mineral Resources should incorporate waste valorization into mining license agreements. Further research should assess the environmental life-cycle benefits of reject re-use and explore advanced beneficiation technologies for slime. This is aligned with the work of [29]-[31], that was carried out a factorial experimental design by flotation, which showed that the interaction between flotation parameters was significant on flotation recovery and concentrate grade. The order of significance was air flow rate, feed size, and sodium silicate dosage. Agitating and scrubbing of flotation feed was very significant on flotation recovery and concentrate grade especially with no grinding because of low phosphate particles liberation. The effect of slimes (fines) generated by such process on flotation performance can be reduced by using column flotation [30].

5.2. Implications for Sustainable Mining and Circular Economy

It can be argued that the high TCP content of coarse reject materials from the A1 and A2 layers demonstrates that their disposal is primarily a consequence of historical processing limitations rather than intrinsic ore quality. Re-crushing and reintroduction of this material into the beneficiation circuit could recover significant phosphate units with relatively modest additional costs. Although slime exhibits higher impurity levels, its moderate phosphate content opens several utilization pathways, including blending with higher-grade concentrates, pelletization for direct agricultural use, or application in specialized low-grade fertilizer products. Slime utilization would also substantially reduce the environmental footprint associated with tailings storage [31].

Integrating reject and slime streams into the production chain aligns strongly with circular economy principles. Such an approach can extend mine life, reduce waste volumes, lower land and water impacts, and enhance the long-term resilience of Jordan's phosphate sector. From a policy perspective, incentivizing waste valorization through regulatory frameworks and mining licenses could accelerate the adoption of sustainable practices [32] [33].

6. Conclusions

This study provides a technically sound and economically realistic foundation for integrating waste valorization into the operational framework of the Eshidiya Phosphate Mine. The results clearly indicate that coarse reject phosphate derived from the A1 and A2 stratigraphic layers possesses sufficient chemical quality and physical characteristics to justify direct reintegration into the existing beneficiation circuit following controlled crushing, with minimal modification to current processing infrastructure. This approach offers an immediate opportunity for reducing primary ore losses, increasing overall phosphate recovery, and lowering unit production costs.

Reject material from the A3 layer, despite its comparatively lower grade, demonstrated a strong response to simple washing and size classification techniques, confirming its potential as a secondary resource rather than waste. The inclusion of this material through a dedicated low-cost washing stage can incrementally increase reserve utilization, while extending the operational life of the mine. Such an approach is particularly relevant under fluctuating global phosphate prices, where marginal resources can become economically attractive.

Furthermore, phosphate-rich slimes containing approximately 46% TCP represent a largely untapped resource stream. When appropriately dewatered and blended with higher-grade concentrates, these slimes can be directed toward low-grade fertilizer production, soil conditioners, or industrial phosphate applications, reducing the environmental footprint associated with tailings disposal and slime pond expansion.

From a sustainability perspective, the proposed waste valorization framework aligns strongly with circular economy principles, emphasizing resource efficiency, waste minimization, and value recovery. The adoption of this strategy by Jordan Phosphate Company can result in: reduced waste disposal volumes and associated environmental liabilities; improved raw material utilization and phosphate recovery rates; lower energy and water consumption per ton of final product, and enhanced compliance with ESG standards and national sustainability goals.

To facilitate implementation, it is recommended that JPMC adopt a phased integration strategy, beginning with pilot-scale trials for A1-A2 reject reintegration, followed by modular washing units for A3 material and controlled slime blending programs. Continuous monitoring of product quality, processing costs, and environmental performance should accompany each phase to ensure technical and economic viability.

In conclusion, waste streams traditionally classified as rejects at the Eshidiya Mine should be redefined as strategic secondary resources. By embedding waste valorization into mine planning and processing operations, JPMC can position itself as a regional leader in sustainable phosphate mining**,** while simultaneously enhancing long-term profitability, resource security, and environmental stewardship in Jordan.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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