Environmental Impact Assessment of Phosphate Mining at Djebel Onk, Algeria Using the Rapid Impact Assessment Matrix (RIAM)

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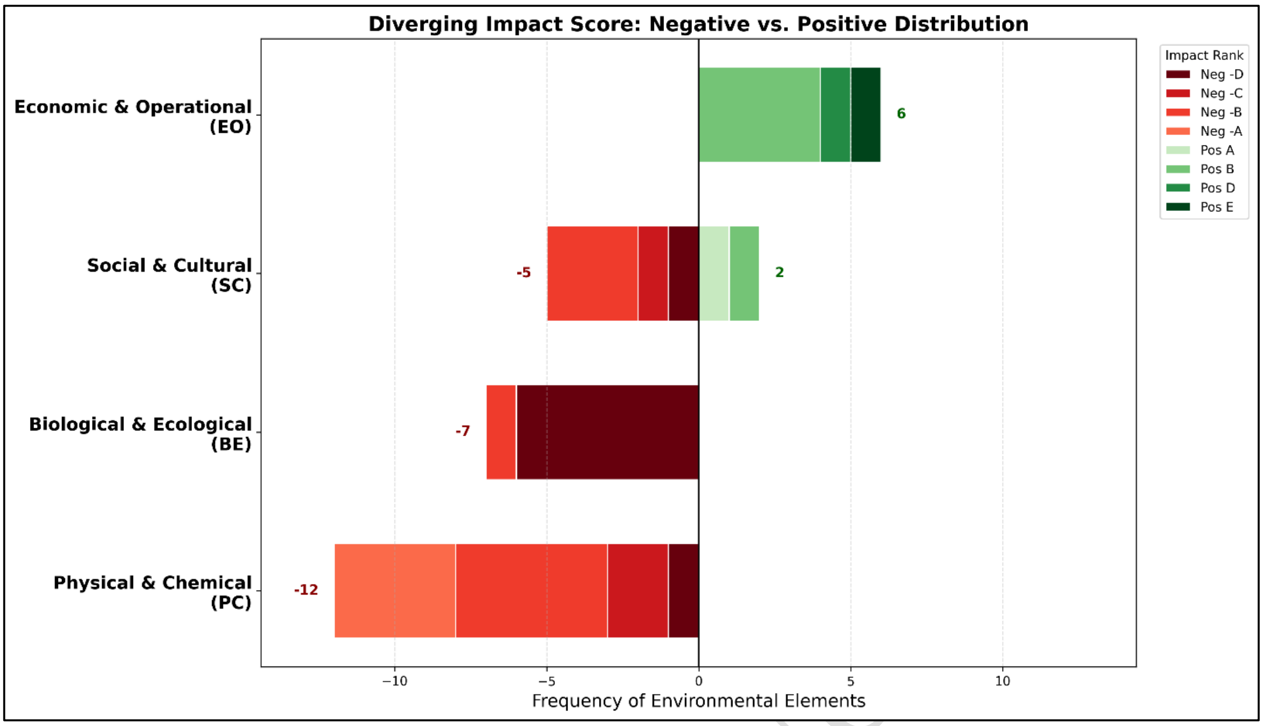
Graphical abstract



Abstract

The environmental impact assessment (EIA) of the Djebel Onk phosphate mine, utilizing the Rapid Impact Assessment Matrix (RIAM), reveals a significant disparity between the substantial economic benefits and serious environmental challenges. The results indicate substantial negative impacts on biological and ecological components, with marked degradation observed in steppe grazing areas, vegetation cover, and faunal diversity. Additionally, moderate to limited adverse effects on air and water quality, as well as public health, were attributed to dust emissions, pollution, and vibrations caused by mining operations. Conversely, the economic and operational factors demonstrated significant positive effects, reflected in support for the national economy, job creation, and improved municipal financial resources. To reconcile these opposing outcomes, the study recommends adopting integrated environmental strategies that prioritize strict risk management, enhanced regulatory monitoring, and the development of pollution reduction technologies. Ultimately, achieving a balance between economic development and environmental preservation requires an urgent, responsible, and sustainable strategy.

Keywords: air pollution, biodiversity, Bir El Ater, dust, public health, sustainability, water pollution

1. Introduction

The environmental impact assessment (EIA) is a systematic process through which the potential environmental and social impacts of a proposed project are identified and evaluated in collaboration between project proponents, environmental authorities, and relevant stakeholders. The primary objective of EIA is to identify the key factors contributing to the project's overall environmental burden and to design appropriate mitigation measures. Central to this process is determining whether the project is likely to cause significant environmental change, a judgment that guides regulatory decision-making. Assessments of impact significance are made throughout all stages of the EIA process, from initial impact identification to the final evaluation of project feasibility by environmental authorities, underscoring the critical role of impact significance assessment in environmental decision-making (Ijäs *et al*. 2010).

Mining operations represent one of humanity’s most significant interventions in natural landscapes, providing essential resources that support economic development while simultaneously generating profound environmental consequences. The extraction of minerals and metals has historically been a cornerstone of industrial development and continues to play a vital role in global economies. According to Mardonova and Han (2023)**,** this economic benefit comes with substantial environmental costs that extend far beyond the immediate mining site.

The environmental impacts of mining encompass multiple dimensions, affecting water resources, air quality, soil integrity, biodiversity, and human health (Aska et al. 2025). These impacts occur at local, regional, and global scales through both direct and indirect environmental pathways associated with mining activities. Driven by increasing global demand for mineral resources, extraction has risen by 55% in less than two decades, intensifying pressure on Earth's natural resources to unsustainable levels. This trend underscores the need for a comprehensive evaluation of mining-related environmental impacts and the implementation of effective mitigation strategies (Boumaza et al. 2024).

Water resources are particularly vulnerable to mining activities; operations can significantly alter hydrological systems through excessive water consumption and landscape modifications. More concerning is the contamination of surface and groundwater by chemicals associated with mining processes. Without proper precautions, elevated concentrations of harmful substances such as arsenic, cyanide, sulfuric acid, and mercury can spread over large areas of surface or subsurface water. The extensive water requirements for mine drainage, cooling, extraction, and processing further increase the potential for chemical contamination. Acid mine drainage represents one of the most persistent water pollution challenges, together with sedimentation and deposition of metals from mining wastes (Damseth *et al*. 2024).

Air quality degradation represents another significant environmental consequence of mining operations. Dust emissions are a common problem throughout mining activities, with specific concerns about fluoride emissions and radon gas in certain mining operations such as phosphate extraction (Mudd 2008). These air pollutants can affect both the immediate mining area and surrounding communities, contributing to respiratory health issues and environmental degradation.

Mining operations inevitably transform landscapes, often resulting in deforestation, habitat fragmentation, and biodiversity loss (Jain *et al*. 2016). The process is inherently invasive, causing damage to ecosystems in areas much larger than the actual mining site. This ecological disruption can persist long after mine closure, contributing to greenhouse gas emissions, flora and fauna mortality, and habitat degradation. The removal of ecologically valuable topsoil containing seed banks during operations such as hydraulic pumping makes vegetation recovery particularly challenging (Aska *et al*. 2024).

The environmental impacts of mining extend to soil contamination and land degradation. Mining waste, including tailings and overburden, often contains toxic substances and heavy metals that leach into surrounding soils, altering their chemical composition and reducing fertility. This contamination can persist for decades or even centuries, rendering land unsuitable for agriculture or natural ecosystem recovery. Mining activities can remove nutrient-rich topsoil and vegetation, leaving land infertile and unsafe for farming (Hilson and McQuilken 2014).

Human health implications represent a critical dimension of mining's environmental impact. Communities near mining operations often experience elevated exposure to toxic metals and radioactive elements. Studies have identified lead, cadmium, mercury, chromium, arsenic, uranium, thorium, and radium as elements of significant human health concern in mining contexts. Many mining communities, particularly in developing countries, are impoverished and lack basic resources such as healthcare services and potable water, exacerbating their vulnerability to mining-related environmental hazards (Quintero Santofimio *et al*. 2024).

The severity of mining's environmental impacts varies considerably based on several factors, including the type of mineral being extracted, the mining method employed, regulatory frameworks, and company practices. Surface mining, underground mining, and seabed mining each present distinct environmental challenges. Similarly, different minerals require specific extraction and processing methods with varying environmental impacts. Phosphate mining, coal mining, lithium mining, and sand mining have been identified as having particularly significant environmental and public health effects (Edo *et al*. 2024).

Phosphate mining is widely studied due to its global importance for agricultural fertilizer production, yet it presents significant environmental challenges. Systematic reviews of phosphate extraction and beneficiation indicate that its impacts are strongly associated with water systems, particularly through high water demand and the discharge of acidic and metal-rich effluents, as well as atmospheric emissions that contribute to air pollution and associated human health risks (Reta *et al*. 2018).

In addition, studies highlight concerns related to acidic process water and the mobilization of toxic metals and naturally occurring radioactive materials from phosphate rocks into the environment. Impacts on aquatic systems include alterations in hydrological regimes due to industrial water use and landscape modifications, along with deterioration of water quality through wastewater discharge (Tian *et al*. 2025).

1.1.Environmental Impacts of Phosphate Mining in Djebel Onk, Algeria

The phosphate mining sector is a key contributor to Algeria's economy, with the Djebel Onk mining complex in Tebessa province representing one of the country's most significant mineral resources (Salhi *et al*. 2023). Operating since 1965, this complex has been essential for various industrial sectors ranging from agriculture to pharmaceuticals and metallurgy (Yahiaoui *et al*. 2024). However, despite its economic importance, the environmental consequences of mining activities at Djebel Onk have raised increasing concerns, particularly regarding their impacts on the surrounding communal territory of Bir El Ater (Boumaza *et al*. 2021).

The environmental impacts of phosphate mining at Djebel Onk are substantial. The continuous discharge of phosphate sludge, containing significant amounts of P_2O_5 alongside various heavy metals and potentially toxic elements (PTEs), without proper treatment has led to significant environmental degradation. Recent studies emphasize that these contaminants threaten local water resources, soil quality, vegetation, and human health, while also posing radiological hazards (Boumaza *et al*. 2021;

Djabou and Belafrites 2023; Hamed *et al*. 2024; Boumaza *et al*. 2023). Such findings underscore the need for comprehensive assessment frameworks that consider chemical, ecological, and socio-economic consequences.

Despite growing recognition of these environmental challenges, there exists a significant scientific gap in the holistic assessment of mining impacts on the Bir El Ater area. While several studies have characterized the physical and chemical properties of the phosphate wastes, limited research has systematically evaluated the spatial extent of contamination and the specific effects on different environmental components using standardized methodologies (Yahiaoui *et al*. 2024). This knowledge gap is further exacerbated by the anticipated expansion of mining activities in the region, notably the Bled El Hadba project, which is likely to amplify cumulative environmental impacts on surrounding territories.

To address this gap, this study employs the Rapid Impact Assessment Matrix (RIAM) to assess the environmental impacts associated with phosphate mining in the Djebel Onk region. To the best of the author's knowledge, this represents the first comprehensive application of the RIAM methodology to this mining complex, providing a baseline assessment framework capable of supporting the evaluation of potential cumulative impacts associated with future mining expansion.

1.2. Research Objectives

To address the identified knowledge gap, this research aims to comprehensively assess the environmental impacts of phosphate mining at Djebel Onk within the Bir El Ater area. Specifically, the study objectives are to:

- establish a regional environmental baseline and characterize current environmental pressures in the Djebel Onk area;
- apply the Rapid Impact Assessment Matrix (RIAM) to evaluate the impacts of mining activities on physical/chemical, biological/ecological, Sociological/cultural, and economic/operational components;

• propose targeted environmental management recommendations aimed at mitigating negative impacts while supporting sustainable development.

Ultimately, this study contributes to the Sustainable Development Goals (SDGs) by providing a structured, scientifically grounded framework for balancing natural resource exploitation with environmental protection (UNDP, 2018).

2. Materials and Methods

2.1. Existing Environmental Impact Evaluation Methods in EIA

Several methods are commonly used to assess the environmental impacts of projects and activities within the EIA framework. The principal approaches include checklists, matrices, the Battelle Environmental Evaluation System, networks, and overlays (Glasson *et al.* 2005; Tianliang *et al.* 2023). Their distinct characteristics, advantages, and limitations are detailed in **Table 1**.

Table 1. Main Advantages and Disadvantages of Impact Identification Methods

Method	Advantages	Disadvantages
Checklists	- Simple to understand and apply - Effective for site selection and priority setting - Simple ranking and weighting	- Do not distinguish between direct and indirect impacts - Do not link action and impact - Incorporation of values can be controversial
Matrices	- Clearly link project activities to environmental impacts - Facilitate the presentation and interpretation of EIA results	- Difficult to distinguish direct from indirect impacts - Potential for double-counting impacts
Battelle System	- Quantitative (allows numerical comparison) - Comprehensive (covers four main categories) - Useful for comparing alternatives	- Complex and time-consuming - Data-intensive - Relies on subjective weighting
Networks	- Links project actions to environmental impacts - Useful for checking second-order impacts - Handle direct and indirect impacts	- Can become very complex beyond simplified versions

Overlays	- Simple to understand and interpret - Effective for evaluating spatial impacts - Useful for site selection	- Can be cumbersome - Poorly suited for impact duration or probability

The selection of the RIAM method was driven by several critical advantages over traditional tools, such as checklists or simple matrices, which are summarized below:

Analytical Rigor: RIAM is particularly suitable for projects with extensive and cumulative impacts, such as mining, due to its ability to integrate both quantitative and qualitative data, thereby providing a more comprehensive assessment than single- criterion tools.

Transparency and Reproducibility: Its structured scoring system, which distinguishes between Group A weighted criteria (permanent conditions) and Group B additive criteria (temporary conditions), ensures a transparent and reproducible framework that helps minimize subjectivity.

Comparison Capability: RIAM enables clear visual and numerical comparisons between different impact categories (e.g., economic benefits from employment versus biological losses in steppe grazing lands) through standardized Environmental Scores (ES) and predefined range bands.

In general, the selection of impact assessment methods depends on the nature and complexity of the project, the type of anticipated impacts, and the need for clarity in presenting results. For projects characterized by extensive and cumulative impacts, such as mining, advanced methods like RIAM are preferred due to their analytical rigor, reproducibility, and ability to integrate both qualitative and quantitative data.

Despite these advantages, it is important to acknowledge the limitations associated with the method. While the Rapid Impact Assessment Matrix (RIAM) provides a structured framework, Pastakia and Jensen (1998) note that the scoring process inherently relies on the assessor’s judgment, making it susceptible to subjective evaluations. This subjectivity is further amplified by the dependence of the weighting system on expert opinion, which may introduce bias if not carefully managed (Ijäs *et al.* 2010). Moreover, the rigid structure of the scoring system can sometimes lead to ambiguity in representing complex environmental processes.

2.2. RIAM Methodology as a Study Design and Approach

This study employed a descriptive analytical approach to assess both the positive and negative impacts of the Djebel Onk phosphate mine operations. The assessment process began with the identification of potential impacts using a comprehensive checklist. Subsequently, the Rapid Impact Assessment Matrix (RIAM), developed by Pastakia and Jensen (1998), was utilized to evaluate and analyze these impacts.

The RIAM method was selected for this study due to its recognized depth, flexibility, and objectivity in environmental assessments. Previous studies have highlighted its transparency and effectiveness in comparing and ranking projects, plans, and programs (Ijäs *et al*. 2010).

The RIAM methodology operates by defining specific evaluation criteria that allow for the assignment of semi-quantitative values. These values yield a systematic and standardized score for each environmental condition. Environmental components are grouped into four main categories (represented as rows), while the assessment criteria are represented as columns within the matrix.

The calculation process involves the following steps:

- Multiplying the scores for Group A to get $\boldsymbol{AT}$ (Eq. 1).
- Summing the scores for Group B to get $\boldsymbol{BT}$ (Eq. 2).
- Multiplying $\boldsymbol{AT}$ and $\boldsymbol{BT}$ to obtain the final Environmental Score $\boldsymbol{ES}$ (Eq. 3):

$$AT = A_1 \times A_2 \tag{1}$$

$$BT = B_1 + B_2 + B_3 \tag{2}$$

$$ES = A_T \times B_T \tag{3}$$

Where:

A_1 and A_2 are scores for Group A criteria.

B_1, B_2, and B_3 are scores for Group B criteria.

ES is the final environmental score for the condition.

2.2.1. Assessment Criteria and Scales

The criteria and their scoring system, as adapted from (Pastakia and Jensen 1998), are summarized in **Table 2**.

Table 2. RIAM Assessment Criteria and Scoring Scales

Criterion	Score	Description
A1: Importance	4	National/international importance
	3	Regional/national importance
	2	Importance to the immediate locality
	1	Local importance
	0	No importance
A2: Magnitude	+3	Major positive benefit
	+2	Significant improvement
	+1	Improvement
	0	No change
	-1	Negative change
	-2	Significant negative change
	-3	Major negative change
B1: Permanence	1	No change
	2	Temporary
	3	Permanent
B2: Reversibility	1	No change
	2	Reversible
	3	Irreversible
B3: Cumulative	1	No change
	2	Non-cumulative
	3	Cumulative/synergistic

2.2.2. Environmental Components

The four main categories of environmental components assessed by RIAM are:

- Physical/chemical (e.g., air, water, soil, noise);
- Biological/ecological (e.g., plants, animals, habitats);
- Sociological/cultural (e.g., population, migration, health, welfare);
- Economic/operational (e.g., employment, income, land prices).

Table 3. Description of Numeric and Alphabetic Range Bands (Pastakia and Jensen 1998)

Range Bands	Alphabetic Range	Environmental Score (ES)	Numeric Range
Comprehensive Positive	E	5	108–72
Marked Positive	D	4	71–36
Moderate Positive	C	3	35–19
Limited Positive	B	2	18–10
Slight Positive	A	1	9–1
No Impact / Change	N	0	0
Slight Negative	-A	-1	-9 to -1
Limited Negative	-B	-2	-18 to -10
Moderate Negative	-C	-3	-35 to -19
Marked Negative	-D	-4	-71 to -36
Comprehensive Negative	-E	-5	-108 to -72

2.3. Case Study: Djebel Onk Phosphate Mine as a Source of Environmental Impact

The Djebel Onk phosphate mine in the municipality of Bir El Ater, Tebessa Province (34°42'23"N, 8°00'11"E), ranks among Africa's largest producers with 2.8 billion tons of reserves and 1 to 1.7 million tons annual capacity (Salhi *et al*. 2023; Yahiaoui *et al*. 2024). Located 7 km south of Bir El Ater town and 97 km from Tebessa city across 897 hectares (Fig. 1), this strategic complex, operational since 1956, plays a key role in Algeria's mineral diversification policy (Boumaza *et al*. 2021).

Geologically, the Djebel Onk mine belongs to a stratigraphic succession dating from the Maastrichtian to the Lutetian periods, covered by Miocene and Quaternary deposits. The phosphorite layer is dated to the Upper Thanetian and is characterized by a thickness of about 35 meters, with a general dip of 10 to 15 degrees southward. Two main facies of phosphorite can be distinguished, differing in color (black and brown) depending on matrix composition and organic matter content. This layer is further divided into three sub-layers based on phosphorus pentoxide (P_2O_5) concentrations: the basal, main, and upper layers. The main layer is particularly significant due to its thickness (about 25 meters) and high P_2O_5 content (>28 wt%), making it the primary source for raw phosphate extraction. The phosphate ore here is predominantly carbonate fluorapatite (CFA), while the host rocks include minerals such as quartz, calcite, dolomite, and clay, along with varying amounts of organic matter and secondary sulfide minerals (Mezghache, 2012; Tahri *et al*. 2023).

Current operations concentrate on Kef Essennoun's eastern slopes (730 – 890 m elevation) using conventional open-pit methods. The sequence includes drilling, blasting, overburden removal, crushing, screening, washing ($P_2O_5 > 28\%$), and rail transport to Annaba port (Yahiaoui *et al*. 2024).

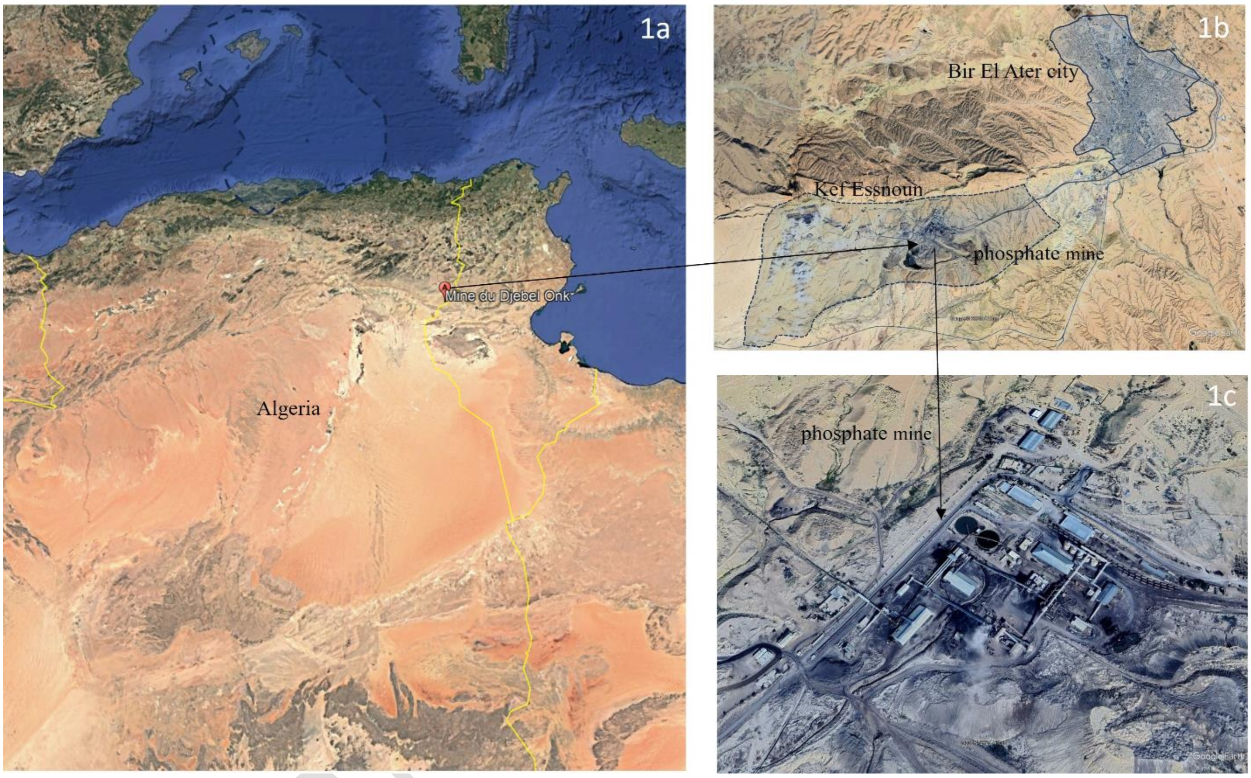


Figure 1. Geographic location of the study area: a. Map showing the geographic location of Djebel Onk phosphate mine; b. Mining exploitation perimeter and the surrounding urban area of Bir El Ater; c. Mining plant

The beneficiation process at the mine generates over 4,000 tons of phosphate sludge (CFA) daily, alongside clays and heavy metals such as uranium (U), cadmium (Cd), and arsenic (As). Wastewater from the washing process poses a significant risk of groundwater contamination, while crushing and transport operations are major sources of particulate emissions. The scale of production, the vast exploited area, and the intensive open-pit mining methods create substantial environmental pressures that necessitate rigorous environmental assessment to understand their cumulative impacts.

Technically, phosphate exploitation at Djebel Onk involves a sequence of interconnected operations, from raw material extraction through processing, handling, and logistics (Fig. 2). Each phase contributes to the overall production chain and generates specific environmental pressures that were evaluated in this study.

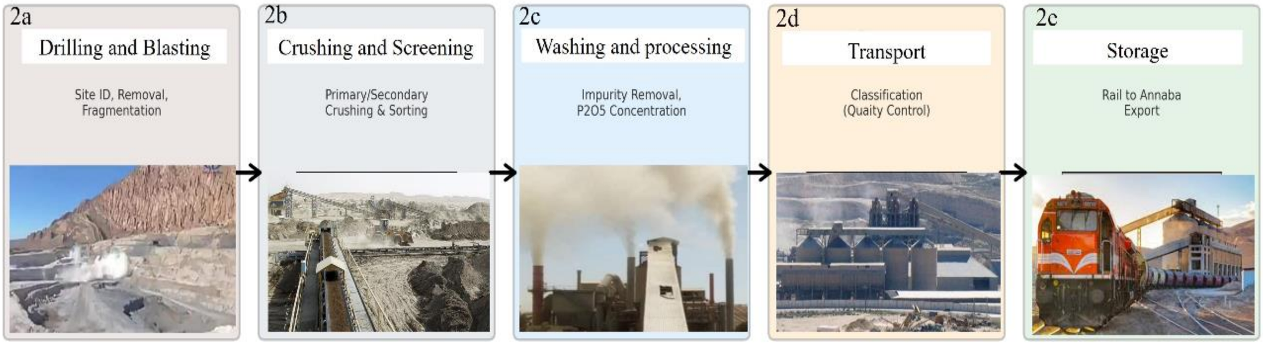


Figure 2. Technical exploitation flowchart of the Djebel Onk phosphate mine, illustrating the sequential stages from extraction to export: a. Drilling and blasting; b. Crushing and screening; c. Washing and Processing; d. Sludge disposal and stockpiling; e. Transport

2.4. Data Collection

The identification of environmental components and spatial boundaries was based on existing territorial planning instruments, namely the Territorial Development Plan of Tebessa Province (PAW) and the Land Use Planning Plan of the Bir El Ater Commune (PDAU). These instruments provide integrated socio-economic and spatial information for land-use regulation under Algerian spatial planning legislation (SPUD, 1990; NTP, 2001), and enabled the structuring of environmental components potentially affected by phosphate mining activities. This inventory process resulted in the identification of 32 environmental elements distributed across the four RIAM assessment groups. The impact zone was defined as a circular buffer area centered on Djebel Onk, with a radius of approximately 25 km. This spatial delimitation was selected to represent the area potentially influenced by phosphate processing operations, including both direct and indirect environmental pressures such as dust dispersion, surface water connectivity, and possible groundwater interactions. Targeted consultations with relevant local institutions were conducted to validate and refine the preliminary assessment. Information on vegetation and biodiversity was obtained from the Forestry

Conservation Directorate, agricultural and soil data from the Agricultural Services Directorate, and hydrological information from the Hydraulics Directorate. Operational and technical data were collected from the Phosphate Mines Company of Tebessa and the Djebel Onk Mining Complex, while regulatory and environmental background information was provided by the Environment Directorate of Tebessa. Field visits complemented the desk-based analysis, allowing direct observation of processing operations, waste disposal sites, and their immediate environmental impacts.

To assign values to the identified environmental impacts, a structured expert elicitation process was conducted. A multidisciplinary panel of 30 experts was selected based on strict, predefined criteria to ensure comprehensive and reliable coverage of all environmental components:

1. Professional Experience: A minimum of five years of active professional experience in environmental, mining, or related sectors.

2. Relevance to the Study: Direct institutional involvement or a professional relationship with the environmental and socio-economic issues associated with phosphate mining in the region.

3. Multidisciplinary Composition: The panel was deliberately structured to encompass diverse expertise (local administration, environmental and water authorities, agricultural and forestry services, health sector, mining company, academia, civil society, and private consultancy) to ensure that all four RIAM categories (Physical/Chemical, Biological/Ecological, Sociological/Cultural, and Economic/Operational) were adequately evaluated by domain specialists.

4. Data Scarcity Justification: Expert judgment was specifically relied upon to bridge the gap caused by the absence of continuous, quantitative field measurements (e.g., real-time air quality indices or exhaustive hydro-chemical datasets), making their experiential knowledge essential for a holistic impact assessment.

To standardize the scoring process, a customized evaluation form based on RIAM criteria (A1, A2, B1, B2, B3) was developed and accompanied by a detailed guideline document. This document explicitly defined the scoring boundaries and the interpretation of each criterion to ensure a uniform understanding across different disciplines. Prior to the formal evaluation, a calibration session (pilot testing) was conducted with a subset of experts. This step was crucial to align the panel's understanding, refine any ambiguous terminology, and ensure methodological consistency before the actual data collection.

The final scoring was conducted independently by each expert to minimize potential peer influence or conformity bias. To manage potential disagreements and prevent extreme scores from disproportionately skewing the results, the individual scores were statistically aggregated using the arithmetic mean. This approach provides a balanced representation of the collective judgment without forcing an artificial consensus.

3. Results and Discussion

3.1. Results

The final RIAM scores were obtained by aggregating individual expert ratings using the arithmetic mean. To assess the reliability of expert judgments and ensure inter-expert agreement, Cronbach's alpha was computed for each RIAM criterion, yielding values ranging from 0.85 to 0.92, with an overall value of 0.87. These results indicate a high level of internal consistency among the 30 expert responses, confirming the reliability of the dataset **(Table 4)**.

Table 4. Reliability Analysis of the RIAM Assessment Criteria Using Cronbach's Alpha

RIAM Criterion	Cronbach's Alpha	Number of environmental elements	Interpretation
A1	0.89	32	Excellent
A2	0.85	32	Good
B1	0.92	32	Excellent
B2	0.88	32	Good
B3	0.91	32	Excellent
Overall Scale	0.87	160	Excellent

Descriptive statistics of the aggregated Environmental Impact Scores (EIS) show a mean value of -11.5 and a standard deviation of 28.4. The high coefficient of variation (247%) reflects the heterogeneous and polarized nature of environmental responses across the study area. Importantly, the 95% confidence interval for the mean (-21.7 to -1.3) lies entirely below zero, statistically indicating a significant net environmental deficit rather than a neutral balance **(Table 5)**.

Table 5. Descriptive Statistics and Uncertainty Analysis of RIAM Environmental Impact Scores

Descriptive Statistic	**Value**
Number of environmental elements	32
Mean Environmental Impact Score (EIS)	-11.5
Standard deviation (SD)	28.4
Minimum EIS	-54
Maximum EIS	81
Range	135
Coefficient of Variation (CV, %)	247%
Confidence Interval for the Mean 95%	-21.7 to -1.3

Furthermore, a One-at-a-Time (OAT) sensitivity analysis was performed to evaluate the robustness of the RIAM outputs against potential subjective biases. By varying the Importance factor (A1) in Group A while keeping other parameters constant, the analysis confirmed that minor variations in input parameters did not significantly alter the final RIAM classification, indicating the stability of the model results.

The following sections present the key Environmental Scores obtained for each environmental component:

3.1.1. Physical and Chemical Elements (PC)

The physical and chemical components generally exhibited negative impacts ranging from moderate to marked severity. Among the 12 assessed elements, (PC1) Dust recorded the highest negative score (-36; Class -D), reflecting the persistent and cumulative nature of dust emissions associated with mining and beneficiation activities. (PC8) Phosphate Transport also showed a marked negative impact (-28; Class -C), mainly related to the frequency of transport operations and their effects on local air quality. (PC3) Industrial Waste recorded a score of -24, while (PC2) Polluted Water, (PC9) Hydrological Network, and (PC10) Water Quality each showed Moderate Negative impacts (-16; Class -C). Although (PC7) Blasting and Vibrations and (PC6) Combusted Gases presented lower scores (-6), their recurrent nature may contribute to chronic environmental pressure within the study area. The detailed RIAM scores for physical and chemical elements are presented in **Table 6**.

3.1.2. Biological and Ecological Elements (BE)

The biological and ecological components exhibited the highest level of negative impact within the study area. The assessment of the seven biological elements indicated substantial ecological disturbance associated with mining activities. (BE2) Steppe Grazing Area recorded the lowest Environmental Score in the assessment (-54; Class -D), reflecting its high ecological importance and the intensity of the observed negative changes.

Similarly, (BE1) Natural Vegetation Cover, (BE3) Orchards and Fruit Trees, and the assessed animal species (BE5, BE6, and BE7) each recorded Environmental Scores of (-36; Class -D). These results suggest significant pressure on local biodiversity and habitat functionality in areas affected by mining operations. Detailed RIAM scores for biological and ecological elements are presented in **Table 6**.

3.1.3. Social and Cultural Elements (SC)

The social and cultural impacts revealed a mixed pattern of negative and positive effects associated with mining activities. (SC1) Public Health recorded a marked negative score (-36; Class -D), reflecting concerns related to environmental pollution and its potential effects on local populations. Similarly, the Psychological Factor of Residents (SC2) showed a significant negative impact (-32).

In contrast, elements associated with financial returns demonstrated positive outcomes. (SC4) Social and Cultural Impact of Financial Return recorded a positive score of +16, while Community Associations (SC5) showed a modest positive impact +8. Cultural Heritage (SC6) and Tourism Activity (SC7), however, recorded Moderate Negative scores (-16), suggesting adverse effects on local cultural and tourism-related values. Detailed RIAM scores for social and cultural elements are presented in **Table 6**.

3.1.4. Economic and Operational Elements (EO)

In contrast to the other assessment families, the economic and operational parameters yielded predominantly positive results, highlighting the economic significance of the mining project. (EO1)

National Economy recorded the highest Environmental Score in the study (+81; Class E), as illustrated in Fig. 3, indicating a substantial positive contribution at the national level. (EO2) Employment Opportunities also showed a strong positive impact, with a score of (+48; Class D). Other operational elements, including the Municipal Treasury (EO3), Financial Subsidies (EO4), and Logistical Support (EO5), recorded positive scores ranging from +12 to +18, reflecting their contribution to local and regional development.

Table 6. Comprehensive RIAM Analysis of Environmental Elements for Djebel Onk Mine

Group	Environmental Element	A1	A2	B1	B2	B3	EIS
Physical and Chemical Elements (PC)	PC1 – Dust	2	-2	3	3	3	-36
	PC2 – Polluted Water	2	-1	3	2	3	-16
	PC3 – Industrial Waste	3	-1	3	2	3	-24
	PC4 – Major Earth Dumps	1	-1	2	2	3	-7
	PC5 – Oils and Hydrocarbons	2	-1	2	2	3	-14
	PC6 – Combusted Gases	1	-1	2	2	2	-6
	PC7 – Blasting and Vibrations	1	-1	2	2	2	-6
	PC8 – Phosphate Transport	2	-2	3	2	2	-28
	PC9 – Hydrological Network	2	-1	3	2	3	-16
	PC10 – Water Quality	2	-1	3	2	3	-16
	PC11 – Site Morphology	1	-1	3	3	3	-9
	PC12 – Landscape	2	-1	3	3	3	-18
Biological and Ecological Elements (BE)	BE1 – Natural Vegetation Cover	2	-2	3	3	3	-36
	BE2 – Steppe Grazing Area	3	-2	3	3	3	-54
	BE3 – Orchards and Fruit Trees	2	-2	3	3	3	-36
	BE4 – Forests	2	-1	3	3	3	-18
	BE5 – Domestic Animal Species	2	-2	3	3	3	-36
	BE6 – Wild Animal Species	2	-2	3	3	3	-36
	BE7 – Protected Wild Animal Species	2	-2	3	3	3	-36
Social and Cultural Elements (SC)	SC1 – Public Health	2	-2	3	3	3	-36
	SC2 – Psychological Factor of Residents	2	-2	3	2	3	-32
	SC3 – Visual Pollution	2	-1	3	3	3	-18
	SC4 – Social and Cultural Impact of Financial Return	2	1	3	2	3	16
	SC5 – Community Associations	2	1	2	1	1	8
	SC6 – Cultural Heritage	2	-1	3	2	3	-16
	SC7 – Tourism Activity	2	-1	3	2	3	-16
Economic and Operational Elements (EO)	EO1 – National Economy	3	3	3	3	3	81
	EO2 – Employment Opportunities	3	2	3	2	3	48
	EO3 – Municipal Treasury	2	1	3	3	2	16
	EO4 – Financial Subsidies	2	1	2	2	2	12
	EO5 – Logistical Support to Municipalities	2	1	2	2	2	12
	EO6 – Public and Private Investments	3	1	2	2	2	18

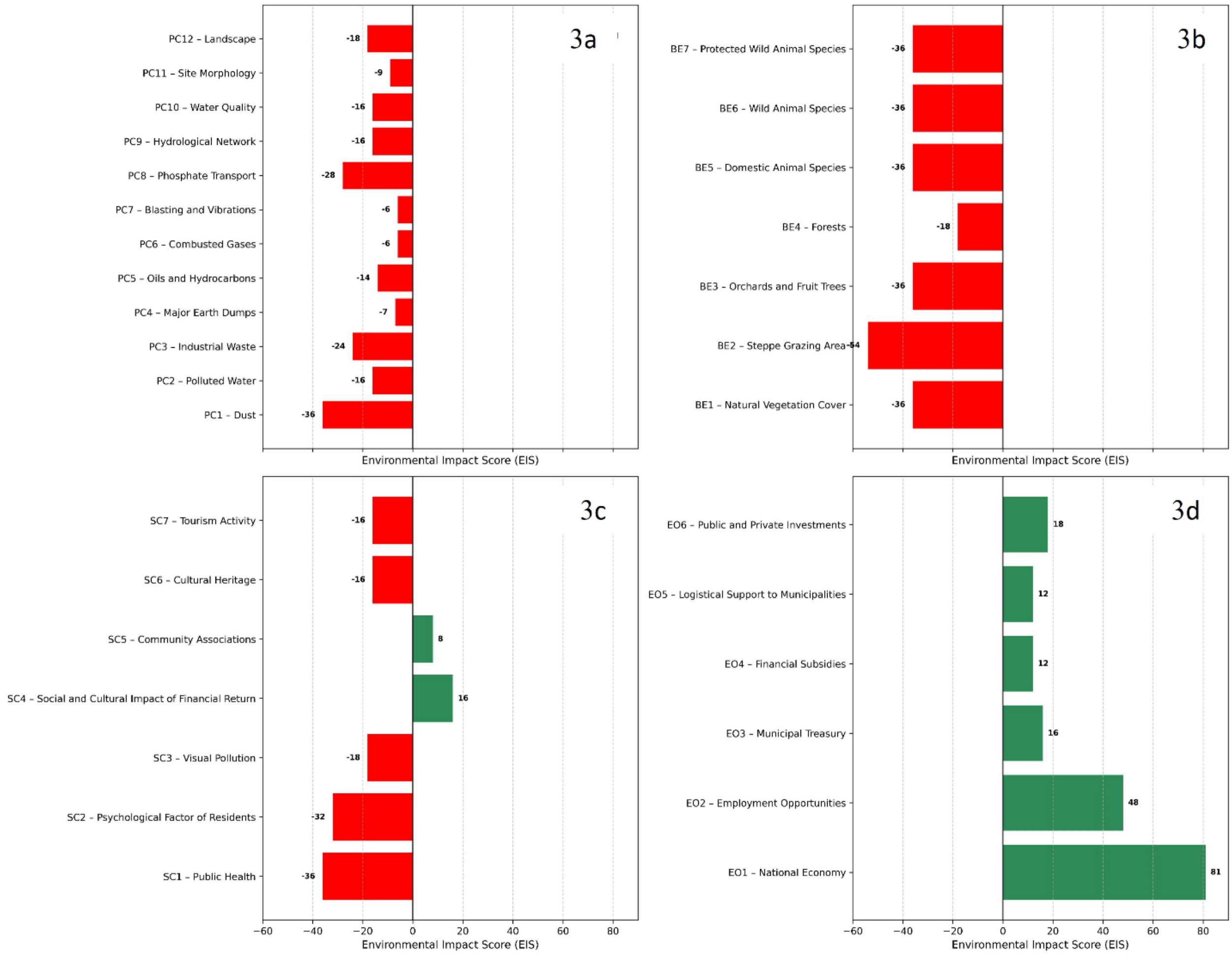


Figure 3. Environmental Impact Assessment Results using RIAM: a. Physical and Chemical Elements (PC); b. Biological and Ecological Elements (BE); c. Social and Cultural Elements (SC); d. Economic and Operational Elements (EO)

3.2. Discussion

The frequency distribution of Environmental Scores presented in **Table 7** and Figure 4 indicates a predominance of negative impacts across the assessed environmental components. Of the 32 evaluated elements, 24 (75%) recorded negative scores, whereas only 8 elements (25%) showed positive impacts. This distribution reflects the dominance of negative environmental effects associated with phosphate mining activities. Overall, these results reveal a net environmental deficit. This imbalance suggests that, despite the economic benefits associated with phosphate mining activities, the current mode of exploitation is accompanied by considerable environmental pressures. To further examine the consistency of the results, comparisons were conducted using available field observations, published regional studies, and relevant international literature.

The most critical impacts are concentrated within the Physical and Chemical (PC) family, which shows a broad dispersion of negative scores, suggesting cumulative and chronic environmental degradation. Regarding air quality, the high negative impact scores assigned to Dust (PC1) and Phosphate Transport (PC8) are consistent with field observations in Bir El Ater, where elevated dust levels are driven by proximity to the mining complex, prevailing southerly winds, and intensive transport activities passing through urban zones.

Similarly, the regional hydrological network appears highly sensitive; recent hydro-chemical data (INSID, 2025) indicate potential signs of water quality degradation, including variations in pH (occasionally < 6) and increased salinity. Consequently, the corresponding impact (PC10) was classified as Moderate Negative (-16), reflecting observed water quality issues alongside limited spatial extent, data uncertainty, and potentially reversible effects. These physical impacts are closely associated with phosphate extraction and beneficiation processes, a pattern that is broadly consistent with findings reported in other phosphate-producing regions. For instance, phosphate processing activities in Tunisia have been associated with significant chemical by-products (Boujlel *et al*. 2018), while elevated levels of environmental contamination, including natural radioactivity accumulation, have been reported in Morocco (Belahbib *et al*. 2021). These comparisons suggest that the PC scores observed in Djebel Onk may reflect a systemic challenge commonly associated with phosphate mining activities at the international scale.

Furthermore, the Biological and Ecological (BE) family accounts for the majority of marked negative impacts (Class -D, **Table 7** and Figure 4), with six out of seven elements falling into this category. Field observations indicate a significant reduction in vegetation cover over recent decades, with the current landscape characterized by sparse, drought-resistant species (approximately 7% vegetation cover), consistent with the strong negative impacts for biological components (BE1, BE2). The study area also shows reduced livestock density and limited diurnal fauna, suggesting habitat displacement. This severe ecosystem stress aligns with local observations by Boumaza *et al*. (2023) and Yahiaoui *et al*. (2024), and mirrors findings in southern Tunisia (Hamed *et al*. 2023). In contrast, the Economic and Operational (EO) family exhibits the highest frequency of positive impacts, reflecting the mine's contribution to national economic development and local employment. However, this highlights a pronounced economic–ecological trade-off, as the ecological damage is highly concentrated locally while economic benefits remain spatially limited (Salhi *et al*. 2023). This trade-off is a common pattern in life cycle assessment (LCA) studies of phosphate mining in the Maghreb region. The Social and Cultural (SC) family further reflects this complexity; negative impacts slightly outweigh positive ones, indicating that while local communities benefit economically, they simultaneously experience health-related pressures. According to local health statistics, 78 cancer cases were reported in Bir El Ater in 2025. While this observation warrants attention, no causal relationship can be inferred from the present study, as it does not include epidemiological analyses. Consequently, further multidisciplinary research is required to investigate potential health outcomes and their possible determinants.

The severity of these impacts is further exacerbated by the inadequacy of current mitigation measures. Present initiatives are largely restricted to outdated dust control systems within the facility, while external efforts remain minimal and sporadic (e.g., occasional tree planting). The absence of regular preventive measures, such as systematic water spraying or comprehensive wastewater treatment, fails to address the chronic nature of the PC and BE impacts, explaining ongoing local concerns.

In this context, the environmental impact patterns identified through the RIAM analysis can be considered indicative of risks that may also arise in the nearby Bled El Hadba Phosphate Project. While site-specific conditions may vary, the similarities in geological setting and processing techniques suggest that comparable environmental pressures could emerge. Therefore, integrating preventive environmental management strategies at the early planning stage of this future project is essential to mitigate cumulative impacts and ensure more sustainable resource exploitation.

Table 7. Final Summary of Environmental Statement (Frequency Distribution of Impacts)

Range of Values	-108 -72	-71 -36	-35 -19	-18 -10	-9 -1	0	1 9	10 18	19 35	36 71	72 108
Rank	-E	-D	-C	-B	-A	N	A	B	C	D	E
Physical and Chemical (PC)	0	1	2	5	4	0	0	0	0	0	0
Biological and Ecological (BE)	0	6	0	1	0	0	0	0	0	0	0
Social and Cultural (SC)	0	1	1	3	0	0	1	1	0	0	0
Economic and Operational (EO)	0	0	0	0	0	0	0	4	0	1	1
Total	0	8	3	9	4	0	1	5	0	1	1

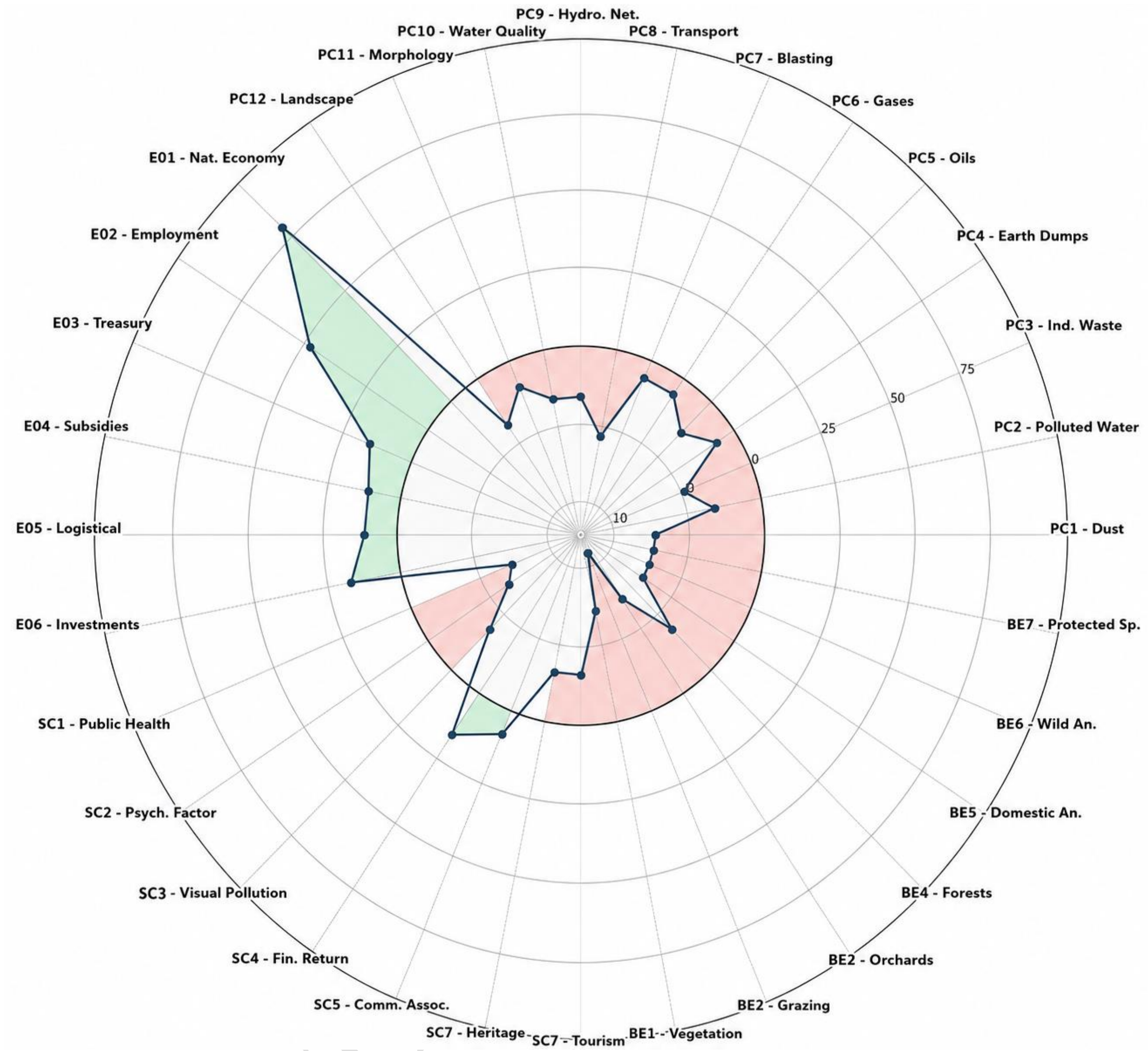


Figure 4. Summary of environmental impact for the Djebel Onk phosphate mine.

3.2.1. Quantitative Balance of the Net Environmental Deficit

To analytically substantiate the concept of the net environmental deficit, a cumulative balance of all Environmental Impact Scores (EIS) was conducted. The aggregate positive impacts, derived primarily from the Economic and Operational (EO) family and limited social benefits, reached a total of +211 points. In contrast, the aggregate negative impacts, encompassing Physical/Chemical, Biological/Ecological, and Sociological/cultural degradation, amounted to -566 points. Accordingly, the resulting Net Environmental Balance for the study area is (-355). It should be emphasized that, although RIAM scores are semi-quantitative and based on ordinal scales, their aggregation in this study is used as an indicative measure to provide an overall view of cumulative impacts. Therefore, the net value (-355) does not represent an absolute quantitative measurement, but rather a comparative index reflecting the dominance of negative environmental pressures over positive contributions. This imbalance highlights a pronounced environmental deficit within the Djebel Onk mining region, where negative impacts substantially exceed the associated economic benefits. The results should thus be interpreted in relative terms, emphasizing the systemic imbalance rather than the numerical value itself.

3.2.2. Study Limitations

While the present study provides a structured semi-quantitative assessment of mining impacts using the RIAM framework, certain limitations should be acknowledged. First, the method relies partly on expert judgment, which may introduce a degree of subjectivity despite the use of predefined selection criteria, standardized scoring procedures, and statistical consistency checks. The reliability indicators nevertheless suggest a satisfactory level of internal consistency among expert evaluations.

Second, the assessment was primarily based on expert evaluations and localized observational data rather than continuous quantitative environmental measurements. The integration of detailed laboratory analyses and long-term monitoring data would further strengthen the study results.

Finally, although the study considered a broad impact zone, advanced GIS-based spatial analyses and environmental dispersion modeling were not included. Future research could integrate spatial modeling and continuous empirical monitoring to improve the representation of temporal and spatial environmental variability.

4. Conclusions

This study applied the Rapid Impact Assessment Matrix (RIAM) as a semi-quantitative, multi-criteria evaluation framework to assess the environmental impacts associated with phosphate mining and beneficiation in the Djebel Onk region. Through the systematic analysis of 32 environmental elements across four thematic groups, the method enabled a structured and reproducible assessment of mining-related impacts.

At the aggregate level, 24 out of the 32 assessed elements (75%) yielded negative impact scores, ranging from slight to significant severity, whereas only 8 elements (25%) demonstrated positive outcomes. This distribution indicates a predominant net environmental deficit associated with the studied mining activities.

The results highlight the inherent trade-offs between economic development and ecological integrity. While phosphate mining provides substantial socio-economic benefits, particularly in terms of industrial development and employment, these gains are accompanied by significant environmental degradation across multiple components.

At the level of environmental categories, the Economic and Operational (EO) components exhibited the most pronounced positive impacts, especially regarding contributions to the national economy and job creation. In contrast, the Biological and Ecological (BE) components were identified as the most severely affected, with widespread and potentially irreversible ecological degradation. The Physical and Chemical (PC) components also revealed persistent deterioration in air and water quality, primarily driven by dust emissions, with cascading impacts on environmental and public health.

From a methodological perspective, this study contributes to addressing a gap in the local environmental assessment literature. To the best of the author's knowledge, it represents the first reported application of the RIAM framework to the Djebel Onk mining complex. As such, it may serve as a baseline reference for future environmental monitoring and impact assessment in the region.

Importantly, the findings also provide a valuable basis for extrapolation to similar phosphate mining developments within the same geological context, particularly the nearby Bled El Hadba project.

Based on the findings of this study, the following recommendations are proposed:

- Dust control measures, including improved filtration systems and the development of vegetation buffer zones around mining areas;

- Optimization of transport systems through the use of covered conveyors and rerouting heavy traffic away from residential zones;
- Implementation of efficient process water treatment and recycling systems to reduce pressure on local water resources;
- Application of phytoremediation techniques using native plant species to support soil restoration and rehabilitation of degraded grazing areas;
- Stabilization of mining waste through appropriate covering techniques to reduce dust dispersion and contamination risks;
- Development and enforcement of post-mining rehabilitation plans to ensure ecological recovery of affected sites.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author used ChatGPT (OpenAI) and Perplexity AI for assistance with language editing and improving the writing style. After using these tools, the author reviewed and edited the content as needed and took full responsibility for the content of the published article.

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