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Article

Assessment of Environmental and Health Impacts in the Mining Sector for Sustainable Natural Resource Management: A Review

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Abstract: The exploitation of natural resources, particularly the mining industry, serves as a powerful economic driver for many countries. However, it also entails significant environmental and health repercussions, including the contamination of water resources, air pollution, soil degradation, biodiversity loss, and respiratory diseases. Assessing these impacts is essential for sustainable resource management, as it enables the identification, mitigation, and monitoring of adverse effects. This article presents a literature review on the environmental and health impacts of phosphate mining, with a specific focus on the Jebel El Onk mining sector in Tébessa, northeastern Algeria a region renowned for its large phosphate reserves. Mining activities in this area release heavy metals (cadmium, lead, mercury, and uranium) that are naturally present in the phosphate rock. These contaminants disperse into the air and water, resulting in detrimental consequences for local health and ecosystems. The article aims to evaluate these impacts in order to propose sustainable mitigation measures that balance the reduction of environmental damage and health risks with the preservation of the economic benefits derived from phosphate mining for regional development. The main mitigation measures identified include blasting optimization, ore processing improvements, wastewater reuse, community awareness initiatives, and the strengthening of regulatory compliance.

Keywords: Phosphate mining, Environmental impact, Public health, Sustainable management, Mitigation measures.

1. Introduction

Natural resource extraction projects including minerals, metals, oil, and gas play a crucial role in the economic development of many countries, providing opportunities for sustainable economic and social growth for local communities. Nevertheless, they also pose significant risks to sustainable development, environmental integrity, and public health [1]. Sustainable mining aims to minimize the negative environmental, social, and economic impacts generated by extraction and processing activities. Assessment strategies for the sustainability of mining operations rely on the measurement, monitoring, and improvement of various environmental performance indicators, thereby making it possible to judge the sustainability of a mining operation. The main environmental sustainability indicators in the mining sector include resource consumption efficiency, reduction of soil disturbance, pollution control, as well as the closure and rehabilitation of end-of-life mine sites [2].

Algeria is a country rich in various valuable substances, most of which remain untapped. The country's mineral resources include significant deposits of iron, lead, zinc, copper, clay, marble, and phosphates [3,4,5,6 and 7]. Phosphate mining, in particular, is prominent in the Bir El Ater region in Tébessa, where proven phosphate reserves are estimated to exceed 2 billion tonnes [8]. These resources are exploited by the Société Minière des Phosphates (SOMIPHOS), a state-run mining company [9]. Phosphate rock, primarily composed of apatite minerals, is a crucial source for agricultural fertilizers, but the mining and processing of these materials pose notable environmental and health risks [10].

Phosphates, specifically the mineral apatite ($Ca_5(PO_4)_3(OH, F, Cl)$), are typically found in sedimentary rock deposits, where they are often associated with impurities such as clay, sand, and other heavy metals [11]. Geochemically, phosphate rocks contain trace elements such as cadmium, lead, mercury, and arsenic, which can leach into the surrounding environment during mining operations. The dissolution of these trace elements into soil and water can contaminate ecosystems and disrupt local biodiversity. The extraction process also generates dust, containing fine particulate matter rich in phosphate minerals and toxic heavy metals, which pose respiratory risks to workers and nearby populations [12].

Mining operations, which include the extraction, transportation, and chemical processing of phosphate rock, have significant implications for the surrounding environment [13]. The most direct impact is on the air quality, where dust emissions during excavation, transport, and storage of phosphate ore degrade atmospheric conditions [14,15]. These airborne particles contain high concentrations of phosphate minerals, which can settle on vegetation, soil, and water bodies, leading to contamination and disrupting the local flora and fauna. Furthermore, chemical effluents from mining and processing operations, which often include acidic solutions and heavy metals, pose risks to groundwater and surface water resources [16]. These pollutants, particularly in regions where groundwater is used for drinking and irrigation, can lead to severe public health concerns, including waterborne diseases and long-term health issues related to exposure to toxic metals [17].

Soil contamination is another critical issue arising from mining activities. The use of explosives to extract phosphate rock can lead to increased fracturing in the surrounding rock mass, enhancing the potential for soil erosion and the spread of pollutants [18,19]. The presence of heavy metals in the soil can inhibit plant growth and contaminate agricultural produce, further affecting local communities' health and food security [20]. Additionally, the alteration of natural landscapes through mining operations can destabilize ecosystems, particularly in regions with fragile biodiversity, such as the arid and semi-arid zones of northeastern Algeria [21].

This study comprehensively assesses the environmental and health impacts of phosphate mining and processing in Jebel El Onk (Tebessa). It identifies pollution sources and risks to local ecosystems and public health, then proposes general sustainable mitigation measures that balance reduced environmental damage and health risks with preserved economic benefits for regional development. The research ultimately provides evidence-based recommendations to mitigate adverse effects while maintaining the economic value of this resource.

2. Materials and Methods

The article is structured as follows. The "Materials and Methods" section provides general information on phosphates, including the conditions for phosphate exploitation and enrichment in Jebel El Onk (Algeria). The "Results" section summarizes data on phosphate rock, extraction and recovery techniques, associations with toxic metals and radioactive elements, and the environmental transfer routes of these pollutants. Finally, the discussion focuses primarily on the environmental impacts of phosphate mining and processing, specifically water pollution, air pollution, and human health risks.

2.1 General information on phosphates

Phosphorus, a vital element for life, is central to biological and industrial processes. As Prof. Dr. Bart highlights, "Phosphorus is the spark of life and the builder of structure," underscoring its role in plant nutrition and biogeochemical cycles [22]. Essential for DNA synthesis, photosynthesis, and energy transfer, phosphorus is indispensable to cellular functions.

The discovery of phosphorus traces back to 1669 when German alchemist Henning Brand first identified it. Its luminescent properties inspired the name "phosphorus," derived from the Greek phosphoros ("bearer of light"). In 1769, Carl Wilhelm Scheele identified phosphorus in animal bones, laying the foundation for its agricultural use. By the 19th century, phosphate applications expanded with guano and, later, natural phosphate deposits discovered in the United States and North Africa [23].

Primarily sourced from apatite [$Ca_5(PO_4)_3(OH,F,Cl)$], phosphates are extensively used as fertilizers to improve soil fertility, often supplemented with ammonium, calcium, or aluminum compounds [24]. However, phosphate mining poses significant environmental and health risks. Excessive phosphates in aquatic ecosystems lead to eutrophication and dystrophication, causing water turbidity, planktonic blooms, and marine dead zones, particularly downstream from estuaries [25].

Heavy metals and radioactive elements further compound these concerns. Phosphate rocks contain cadmium (up to 87 mg/kg), uranium (up to 390 mg/kg), and other toxic elements like chromium and mercury, which can leach into soils and water, threatening ecosystems and public health. Additionally, mineral phosphates are fluorine-rich, with concentrations exceeding 3%, posing risks such as fluorosis in livestock grazing on treated soils [26].

China, Morocco, and the United States dominate global phosphate production, accounting for over 70% of supply. Morocco alone holds over three-quarters of the world's confirmed reserves, cementing its strategic role in the industry [27]. As demand for phosphates grows, addressing their environmental and health implications remains critical for sustainable management [28].

2.2 Geographic and Geological Overview

The Jebel El Onk mining region is located in southeastern Algeria, approximately 100 km south of Tébessa and 20 km from the Algerian Tunisian border, along National Highway RN16. It forms the natural boundary between the Constantine Plateau and the Sahara Desert (Fig. 1). The Jebel El Onk massif, a prominent limestone range about 20 km long, peaks at 1,198 m at Djebel Tarfaya [19].

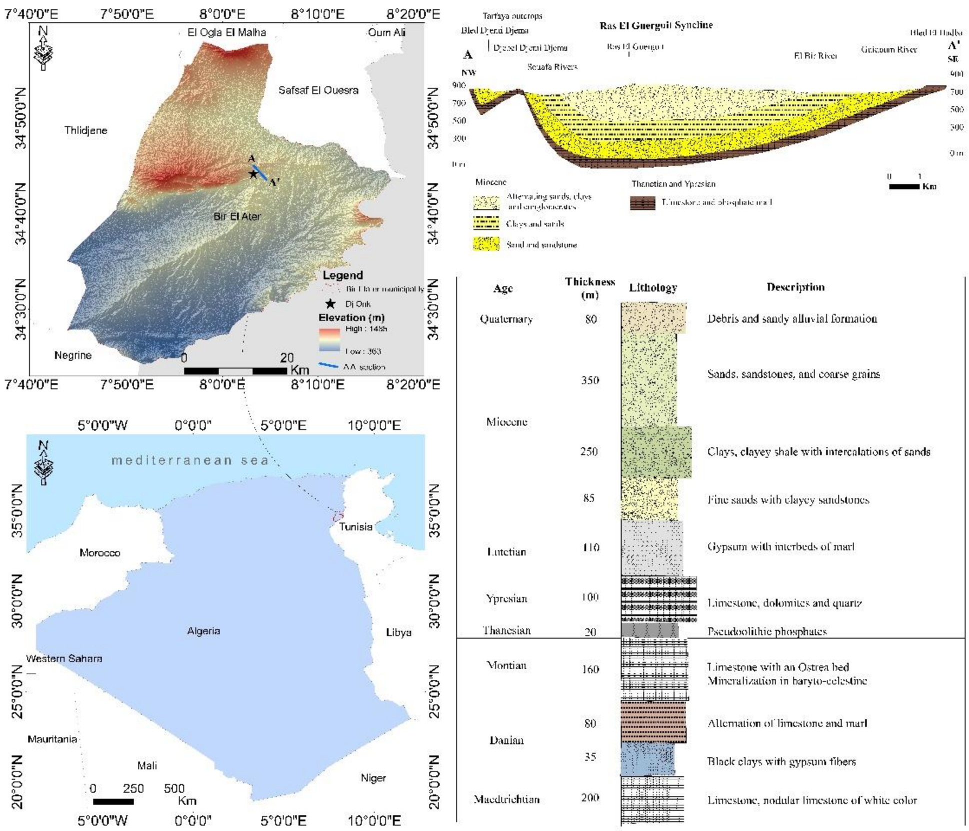

Fig.1. Geographic location, geological cross-section, and litho-stratigraphic log of the study area [19].

This region encompasses multiple mining zones, including Bled El Hadba, Djebel Onk South, Djebel Onk North, and Oued Betita, characterized by diverse lithological and petrographic features. The Upper Thanetian formations, hosting the primary phosphate deposits, outcrop along a northeast-southwest band and overlie Ypresian dolomitic limestone with flint nodules and Lower Thanetian marls [29]. These formations exhibit a westward dip, concealed under Miocene sands (Fig. 1).

Geochemically, Jebel El Onk phosphates contain carbonated fluorapatite and alkaline earth fluorinated sulfocarbonates, along with an endogangue comprising opal, quartz, illite, organic matter, and trace oxides [30].

The exogangue features minerals such as dolomite, quartz, feldspar, and glauconite, highlighting the economic and geological complexity of these deposits [31].

The broader geological context reveals stratigraphic sequences from the Late Cretaceous (Maastrichtian) to the Middle Eocene (Lutetian), capped by Miocene and Quaternary deposits [18]. Maastrichtian formations comprise white flint-bearing limestones transitioning to Danian marly clays and limestones (Figure 1). The Upper Thanetian unit, the main phosphate host, consists of dark gray marls overlain by phosphorite rich dolomites up to 72 m thick, thinning northward. The sequence extends into Ypresian alternating limestones, marls, and phosphates, and Lutetian chalky marls with quartz geodes and flint nodules (Fig. 1) [32].

Miocene terrigenous deposits include conglomerates, sands, and silty clays, culminating in sandy layers and gravelly sandstones. Quaternary deposits, comprising slope debris, gravels, and alluvial-fluvial materials, extensively cover the area (Figure 1) [33].

This geological framework elucidates the stratigraphic, spatial, and mineralogical attributes of the Jebel El Onk phosphate deposits, underscoring their resource potential and implications for mining operations and environmental management.

2.3 Overview of phosphate exploitation and processing at Jebel El Onk

The Kef Essennoun deposit at Jebel El Onk is the primary phosphate reserve exploited by SOMIPHOS, following the depletion of other zones like Djebel Djmijma. Mining at Kef Essennoun employs open-pit methods with a fully mechanized system optimized for the deposit’s geological and structural characteristics [34] (Fig. 2).

The process includes three stages: controlled drilling and blasting for precise fragmentation, mechanized loading and transportation to minimize material loss, and systematic waste management, ensuring non-phosphatic materials are disposed of appropriately while phosphate-rich ore is processed [35].

Fig.2. View of the Kef Essennoun pit at Jebel El Onk.

The phosphate beneficiation plant near Bir El Ater processes raw materials from Kef Essennoun, enhancing the P_2O_5 content through integrated mechanical, wet, and dry treatment methods (Fig. 3). Mechanical preparation (crushing, grinding, and screening) optimizes particle size for downstream processes. Wet treatment focuses on scrubbing and drying to remove impurities, while dry methods involve attrition grinding, turbo separation, and screening to improve ore quality further [36]. These processes eliminate undesirable materials such as carbonates, silicates, and clays, yielding high-grade phosphate suitable for fertilizers and industrial applications.

Fig.3. View of the processing plant.

3. Results and discussions

3.1 Mineralogical and geochemical analyses

The mineralogical and geochemical analyses of phosphate ores from Djebel Onk provide a comprehensive understanding of their composition, mineralogy, and trace element distribution, which are essential for assessing their quality and potential applications.

The mineralogical analysis reveals that the phosphate ores are predominantly sandy, grain-based phosphates, primarily consisting of pseudooliths and pellets, often supported by organic structures such as diatoms and radiolarians[33]. The grain size of these phosphates generally falls within the arenite class (grains smaller than 2 mm), forming biophospharenites, while rudites (grains larger than 2 mm) are less frequent, forming biophospharenorudites. The textures are either homogeneous with fine grains (200–300 μm) or heterogeneous, exhibiting a mix of fine and coarse grains (ranging from 2–3 mm) [9,10]. These ores are lithified and cemented by clay, calcite, or dolomite cement, with accessory minerals such as quartz and glauconite being rare. Diatoms and radiolarians are crucial in the formation of pseudoolithic phosphates [37].

The phosphates consist of phosphatic material and exogenous gangue. For instance, in the Djemi Djema deposit, the phosphatic material includes carbonate fluorapatite and a sulfocarbonate fluorinated alkaliearth phase, sometimes hydrated, with the chemical formula $(S, C, O_4)_6(K, Na, Ca, Mg)F_2 \bullet nH_2O$ (Figure 6). The endogangue, representing about 5.3% of the phosphatic material, consists of opal, quartz, illite, water, organic matter, and trace amounts of accessory elements. This endogangue contains very low quantities of Al_2O_3, Fe_2O_3, MgO, and SiO_2, with each averaging only 0.3% of the total ore [24].

The exogenous gangue comprises three primary components:

1. **Carbonates:** Primarily dolomite.
2. **Sulfates:** Traces of epsomite ($MgSO_4 \bullet 7H_2O$).
3. **Silicates:** Including free silica such as quartz, opal, or amorphous silica, as well as feldspar, heulandite, glauconite, and illite.

Despite the 30 (m) thick phosphate layer appearing homogeneous, significant vertical and lateral facies variations are present. Two main types of phosphate facies are identified:

- **Coprolithic Biophospharudites:** These phospharenites have heterogeneous grain sizes (ranging from 250 µm to over 1 mm), with a cementation of dolomite and calcite, resulting in a hard ore that is sometimes soft and poorly cemented.
- **Pseudooolithic Phospharenites :** These have a finer, more homogeneous grain size (100–300 µm) and are primarily cemented by clay, leading to a soft and friable ore, although carbonate cement may also be present.

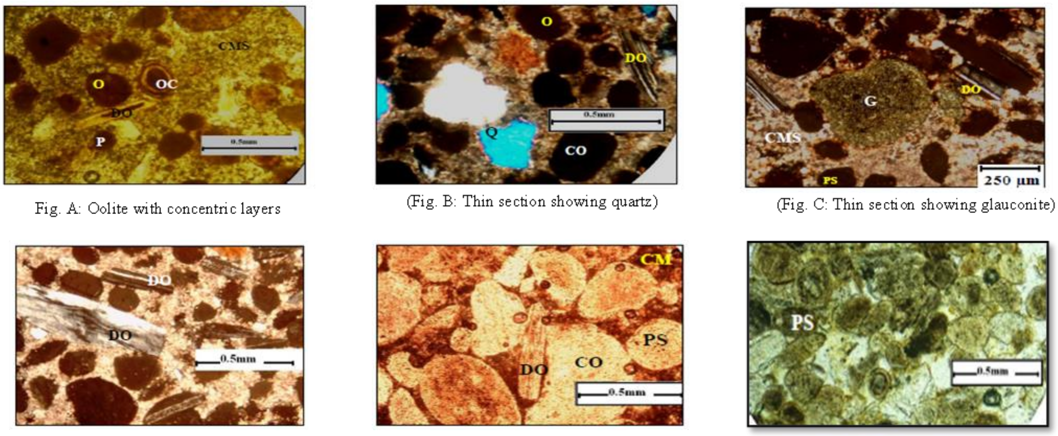

Fig. A: Oolite with concentric layers

(Fig. B: Thin section showing quartz)

(Fig. C: Thin section showing glauconite)

(Fig. D: Bone debris (BD))

(Fig. E: Coprolitic phosphate)

(Fig. F: Pseudo-oolithic phosphate)

Fig.4. Thin sections photography of field simple. O: Oolite; OC: Oolites in concentric layers; P: Pellets; Qz: Quartz; CO: Coprolith; DO: Bone debris; PS: Pseudooolite; G: Glauconite; CM: Micritic cement; CMS: Microsparitic cement.

In addition to the mineralogical composition, the geochemical analysis reveals the presence of trace elements that are concentrated in various mineral phases. Key trace elements include uranium (U) and strontium (Sr), primarily found in the apatite, as well as sodium (Na), barium (Ba), vanadium (V), nickel (Ni), cobalt (Co), chromium (Cr), zinc (Zn), copper (Cu), scandium (Sc), and zirconium (Zr), which are concentrated in the clay minerals. Rare earth elements (REEs) such as yttrium (Y), lanthanum (La), cerium (Ce), europium (Eu), ytterbium (Yb), and lutetium (Lu) are predominantly located in the apatite and bone debris. Cobalt (Co) and manganese (Mn) are often found as oxides and hydroxides accompanying iron compounds, and cadmium (Cd) is mainly associated with dolomitic carbonates in the gangue [38,39,40].

These mineralogical and geochemical characteristics are essential for understanding the formation, distribution, and industrial potential of the Djebel Onk phosphate ores. The correlation between mineral composition and trace element distribution provides insights into the processes of ore formation and their implications for future exploitation.

3.2 Environmental and health Impacts of Phosphate Mining: A Comprehensive Analysis

Phosphate mining significantly impacts both the environment and public health. The various stages of extraction, processing, and beneficiation contribute to multiple environmental challenges, including air, water, and land pollution, as well as noise and vibrations. This study evaluates the environmental consequences of mining activities at Jebel El Onk, focusing on air quality, water resources, ecosystem degradation, and other associated impacts.

3. 2.1. Impact on Air Quality

Phosphate mining emits substantial quantities of dust, gases, and fumes during operations (Fig. 3). Open pit mining at Jebel El Onk exacerbates atmospheric imbalances due to explosive blasting and heavy vehicle traffic. Dust particles, transported by wind over long distances, settle in nearby villages, causing significant environmental and health concerns [19] . These fine particles, often containing silicates, carbonates, and other contaminants, reduce air quality and pose risks to respiratory health, especially for mine workers and local populations.

Combustion of fossil fuels, particularly diesel, further contributes to atmospheric pollution. Emissions of nitrogen oxides (NO), carbon monoxide (CO), hydrocarbons (HC), and lead oxides (PbO) not only degrade air quality but also intensify greenhouse gas effects, leading to climate change and ozone depletion. Long term exposure to these pollutants has been linked to severe health risks, including cancer and respiratory diseases [41].

3. 2. 2. Impact on Water Resources

Mining operations at Jebel El Onk impact water quality and availability through surface runoff and dust accumulation, raising suspended solids in water bodies (Fig. 5). Open-pit mining and beneficiation expose materials to oxygen and water, causing acid mine drainage, which leaches heavy metals and phosphates, degrading water systems.

Fig.5. Liquid effluent discharge from the phosphate desliming process

The beneficiation process, particularly washing, consumes approximately four tons of water per ton of enriched phosphate. This generates waste slurries containing 20% fine solids, which, if improperly managed, pollute local water resources, exacerbating environmental and water scarcity challenges.

3. 2. 3. Impact on Flora and Fauna

Phosphate extraction significantly alters landscapes, creating voids and destabilizing ecosystems, leading to biodiversity loss (Fig. 6). Consequences include habitat disruption, reduced ecological value, increased landslide and subsidence risks, and safety hazards for humans and wildlife near mining sites due to terrain instability and structural fissures.

Fig.6. Soil profile degradation in the Jebel El Onk region due to mining activities

3. 2. 4. Noise and Vibration Impacts

Noise pollution arises from heavy machinery operations, such as trucks, loaders, and drilling rigs, as well as explosive blasting. Prolonged exposure to high noise levels can cause psychosomatic disorders and hearing loss among workers [42]. For nearby residents, persistent noise disturbs daily life and mental wellbeing. Blasting operations generate vibrations that compromise the structural stability of buildings, infrastructure, and natural formations [19]. These vibrations pose risks to both human and animal populations, causing behavioral disturbances and, in severe cases, structural damage in surrounding areas.

3. 2. 5. Impact of Phosphate Mining on Health

Phosphate extraction poses significant health risks due to heavy metals and toxic substances, including fluorine, cadmium, lead, silica, and radioactive minerals [27]. Fine rock dust from mining operations blasting, loading, transportation, drying, and grinding releases pollutants, including uranium-238 and radium-226, which pose inhalation risks during radioactive cloud dispersion [39].

Phosphate ore contains approximately 4% fluorine, contributing to contamination near mining waste discharge points and processing plants [18]. Fluoride contamination affects surface water, groundwater, and marine ecosystems, causing dental fluorosis, also known as (golden tooth disease) from excessive exposure.

These pollutants, along with fine dust emissions, have been classified based on their toxicity and potential harm to human health, emphasizing the urgent need for monitoring and mitigation strategies to minimize their impact on local populations and ecosystems [29] . The associated risks emphasize the importance of balancing phosphate extraction with sustainable environmental and public health practices.

4. Some Proposals to Limit the Negative Effects

The negative impacts of phosphate mining stem from several factors. Updating geological and advanced mineral exploration studies in future mining areas is essential to assess their potential before extraction. This would facilitate the choice of extraction method, optimize operational start-up, and ensure a high ore recovery rate. Efficient operations and advanced processing technologies maximize resource recovery while boosting regional production and economic growth.

Environmental monitoring programs must be implemented to reduce dust emissions, protect the water table, and maintain geotechnical stability. Future strategies must prioritize sustainability and resource optimization to ensure long-term operational and environmental integrity. Mining sites require end-of-life rehabilitation. Authorities must ensure the rehabilitation of abandoned sites, including measures such as perimeter fencing. Furthermore, old mines can be transformed into geoparks through appropriate rehabilitation and subsequently opened to tourists.

5. Conclusion and recommendations

The mining of phosphate and its associated impacts represent a multifaceted issue that demands thorough consideration, particularly regarding its effects on water resources, air quality, and human health. This study highlights the critical challenges posed by phosphate extraction, with a focus on these key areas.

The primary impacts on water resources stem from alterations in hydrology due to the significant water demands of the phosphate industry and landscape modifications. Air quality issues are largely attributed to dust emissions, with the most concerning pollutants being fluoride and radon released during mining operations. For human health, toxic metals and radioactive elements such as cadmium (Cd), chromium (Cr), arsenic (As), and uranium (U) present significant risks due to their presence in phosphate products.

Assessing these effects is the central pillar of the transition toward sustainable natural resource management, especially for phosphate ore, enabling a shift from traditional mining to a responsible approach focused on impact mitigation. To this end, the following recommendations are proposed:

- **Optimization of the Blasting Process:** Implementing enhanced blasting techniques, particularly by using the minimum necessary amount of explosives to achieve the desired fragmentation, along with the use of innovative techniques and modern machinery, helps reduce vibrations, limit the release of harmful gases, and minimize the environmental dispersion of pollutants.
- **Optimization of the Ore Processing Framework:** The integration of innovative and eco-friendly technologies minimizes waste generation and significantly reduces the environmental impact of operations.
- **Improved Waste Management:** Mining companies should adopt advanced waste management practices, including the implementation of appropriate effluent treatment systems before discharge.
- **Wastewater Reuse:** Promote innovative solutions to enable the reuse of treated wastewater, reducing environmental and resource pressure.
- Community Awareness: Educate populations living near polluted areas about the importance of safeguarding wells and food supplies from dust contamination.
- **Regulatory Compliance:** Ensure strict enforcement of regulations governing the disposal of industrial waste into the environment, with active oversight by public authorities.

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