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Review article

Environmental and Health Risks Associated with Metallic Trace Elements Pollution from Abandoned Mine Lands in Morrocco: A review

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Abstract

The amount of mining waste containing metallic trace elements (MTE) is continuously rising because of the high demand for metals in industries, despite the significant risks that mining industries pose to the environment and public health, especially when the site is neglected without proper restoration measures after it has been closed. In this study, we conducted a review to provide a concise overview of the environmental and Human health issues caused by MTE originating from abandoned mining waste in Morocco. Additionally, we aimed to examine the solutions adopted or suggested in scientific research to solve these issues. To reach this, we utilized Scopus, Web of Science, PubMed, and regional databases, applying stringent inclusion and exclusion criteria to identify research publications from the past two decades. A detailed analysis of the studies revealed a correlation between the leaching of MTE from abandoned mine wastes and environmental problems such as the contamination of sediments, soils, waters, and crops. The predominant solutions suggested were biological methods, with a particular emphasis on phytoremediation and bioremediation, and physical and chemical treatment that often have limitations in terms of cost, efficiency, and potential negative impacts on the environment. In conclusion, bioremediation is an emerging and sustainable technology that harnesses microorganisms' abilities to degrade or transform pollutants into less harmful forms. As environmental challenges increase, this approach offers a promising, eco-friendly solution for pollution management. Future efforts should focus on advancing research, optimizing microbial processes, and implementing pilot projects integrating bioremediation into broader environmental strategies to realize its full potential.

Keywords: Environmental law; Environmental pollution; Heavy Metals; Land Restoration; Bioremediation

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Abbreviations:

AMD: Acid Mine Drainage
AML: Abandoned mined lands
BRPM: Office of Mining Research and Participation (Bureau de Recherches et de Participations Minières in French)
MTE: Metallic Trace Elements
MTEDD: Ministry of Energy Transition and Sustainable Development - Department of Sustainable Development (Ministère de la Transition Energétique et du Développement Durable - Département du Développement Durable- in French)
MVT: Mississippi Valley-Type
PANVRM: National Action Plan for the Valorization of Mining Waste (Plan d'Action National pour la Valorisation des Rejets Miniers in French)
SDR: Storage, Diversion, and Release
SMB: Mining Company of Bramram (Société Minière de Bramram in French)
SMEMIC: Moroccan Company for Mining and Commercial Exploitation (Société Marocaine d'Exploitation Minière et Commerciale in French)
SMMPC: Moroccan Company of Mines and Chemical Products (Société Marocaine de Mines et de Produits Chimiques in French)
SMR: Rehamna Mining Company (Société Minière de Rehamna in French)
SNIMM: National Company for Moroccan Mining Industry (Société Nationale de l'Industrie Minière Marocaine in French)
SODECAT: Anti-Atlas Copper Exploitation Company (Société d'Exploitation du Cuivre de l'Anti-Atlas in French)

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1. Introduction

Moroccan's mining industry is a significant economic driver, contributing substantially to its gross domestic product and employment. According to the Ministry of Energy Transition and Sustainable Development of Morocco - Department of Sustainable Development- (MTEDD) in its National Action Plan for the Valorization of Mining Waste (Plan d'Action National pour la Valorisation des Rejets Miniers [PANVRM] in french) (MTEDD, 2021). It has approximately 259 mines, of which 165 are closed. These mines have generally been abandoned without implementing measures to mitigate environmental and safety risks associated with discharges, structures, and infrastructure (MTEDD, 2021). Abandoned mine lands (AML) are defined as lands mined for coal or minerals, abandoned inadequately reclaimed, and where no individual or company is responsible for the site's reclamation. The mining activities left behind approximately 3.5 billion tons of waste between 1968 and 2015, a volume that could double by 2030, exacerbating severe environmental and health impacts such as contaminated drainages, toxic dust dispersion, and landscape disturbances (Khalil et *al*., 2013; Nouri and Haddioui, 2016a). It was effectively shown that mining operations and other anthropogenic activities release many heavy metals into sediments, soils, surface, and groundwater and may hurt the environment and human health (Moubchir et *al*., 2023; Ougrad et *al*., 2024; Rezouki et *al*., 2024). The idea of heavy metals or trace elements is industrial, primarily based on practical experience, and states that these elements are often transition metals with a density exceeding 5 g/cm^3 (Zitka et *al*., 2013). Currently, the designation "heavy metal" has been superseded by "metallic trace elements" (MTE) since certain trace elements, such as Cd, Cr, Zn, Pb, and Cu, can be classified as metals but are not necessarily characterized as "heavy"(Alloway, 2013). Arsenic is poisonous metalloid element but does not possess metallic properties (Ali et *al*., 2019). MTE are primarily present in the environment in trace quantities. They can be classified as natural, from rocks, soil, and water, or anthropogenic, resulting from industrial, mining, and agricultural activities (Ali et *al*., 2019; Laghlimi et *al*. 2015). MTE can either remain locked in the solid phase of soils or be moved to other parts of the ecosystem such as surface water, groundwater, and plants. According to Alloway (2013), elements are categorized as essential or non-essential based on their involvement in biological functions. Organisms require essential elements such as Zn, Fe, Cu, Co, Mn, Ni, Cr, Se, and Mo because they play important roles in various physiological and biochemical functions, including enzymatic activities, electron transfer in photosynthesis, and the respiratory chain (Faouzi et *al*., 2023; Rezouki et *al*., 2023). These elements are crucial in minute amounts, and elevating their concentrations in the environment might result in harmful effects. Nevertheless, non-essential elements such as Cd, Hg, Pb lack any biological function and possess a significant level of toxicity towards various forms of life, including people, animals, plants and microorganisms. These elements demonstrate hazardous properties even at low concentrations for both humans and a wide range of plant and animal species (Alloway, 2013).

Faced with these issues, the Moroccan mining sector requires immediate and effective actions to manage the consequences of mining operations. Law 33-13 was a step forward, establishing crucial measures to address these problems. However, to make the impact tangible, it is necessary to strengthen this legislation with rigorous implementation texts and clear guidelines to ensure complete and effective implementation. In this context, the Department of the Environment has set up a PANVRM, which targets the rehabilitation and valorization of nine priority mining sites, such as Sidi Boubker, Zaida, and others. This plan aims to improve the environmental situation of mining liabilities and establish innovative practices for the management and sustainable valuation of mining heritage. It represents an effort to transform environmental challenges into opportunities for sustainable development, thereby reducing pressure on natural resources and improving the quality of life for local communities (Dessertine, 2023; MTEDD, 2021).

Unfortunately, some sites, Unfortunately, some sites, such as Tansrift, M'fis, and Ouichane, have not yet benefited from these initiatives and continue to degrade the environment, and posing serious risks to human health. MTE contamination in these regions has been documented in various studies (Abdellaoui et *al*.. 2023; Barakat, 2022; Moubchir et *al*., 2023) , highlighting the severity of water and soil pollution and the necessity to adopt advanced remediation techniques. The techniques that have been the most studied are phytoremediation and bioremediation, which look like good ways to clean up and stabilize polluted areas, using plants and microorganisms, respectively, to handle and store MTE, along with geophysical methods to find decontamination pathways and create targeted clean-up plans (Ibouh et *al*., 2011a; Moubchir et *al*,. 2023; MTEDD, 2021).

This study aims to assess the persistence of the MTE in water and soil systems, evaluate the efficacy of current restoration efforts, and offer recommendations for better site management. The study enhances the debate on sustainable mining practices and environmental preservation in Morocco by identifying deficiencies in implementing environmental regulations and examining the prospects for future restoration initiatives.

2. Occurrence of Abandoned Mine Lands in Morocco

Out of the 165 closed mining sites, our bibliographic research identified 19 AML that remain abandoned without remediation, posing significant risks to health and the environment. The geographical locations of these AML are presented in Figure 1, with additional details provided in the appendix A. These sites were classified based on their geographical distribution, arranged from south to north across Morocco, as described below. The numerical identifiers assigned to each site on the map (Figure 1) correspond to the order of classification in the paragraph subtitles that follow, ensuring clarity and ease of reference.

2.1. The Touroug-El Hamda Fluorite Mine

El Hamda Mine, located at 45 km east of Tinjdad in Errachidia province, was a deposit of fluorite and barite in the Ougnat Massif. Fossil sellers initially exploited the mine, but in 2003, the SNIMM company began industrializing the ores for the cement industry. The mine has been closed since 2007, and the region has become

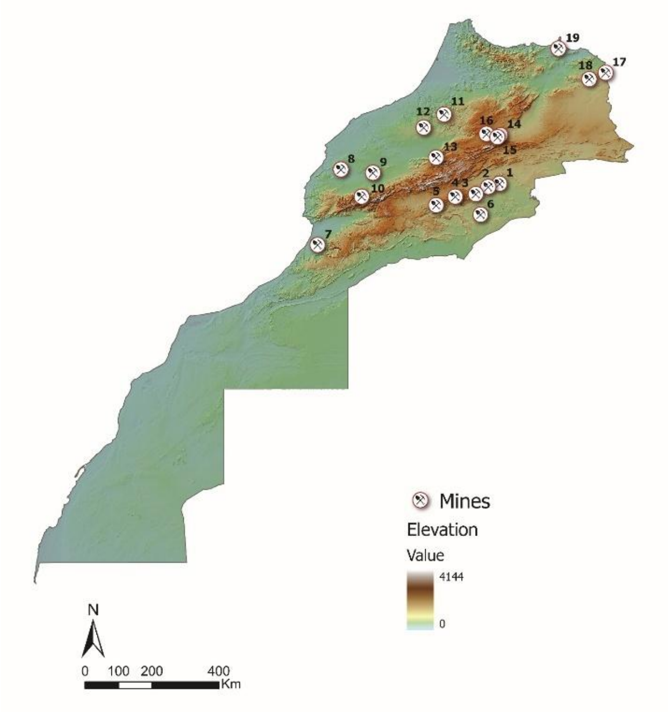

Figure 1: Abandoned Mine Lands in Morocco with Environmental Issues

dominated by intermittent exploitation of valuable substances or metals (Raddi et *al*., 2011a).

2.2. The Bou-Madine Mine

This mine is located in the Precambrian Ougnat inlier, at 15 km South East of Tinejdad, and is home to several epithermal veins with Fe, Pb, Zn, and Cu sulfides, containing significant amounts of Ag, Au, and Sn. The deposit was formed due to the interference between magmatic episodes and shearing regimes during the late Pan-African phase. The rhyolitic intrusions and mineralization occurred due to the permanence of the shearing regime and extension. The deposit was known since the Middle Ages, with the rediscovery dating back to the late 50s. The Mine was recently closed (Abia, 2011).

2.3. Imi n'Tourza Oolithic Iron Mine

The Imi n'Tourza deposit, located at 15 km north of the Tineghir-Alnif road (south of Saghro mountain), is an oolitic iron deposit in the Saharan platform. It is the largest deposit in the Moroccan Ordovician, with reserves of around 40,000,000 tons. It was first reported in 1944 and was first exploited by the Mokta-el-Hadid Magnetic Iron Ore Company (Compagnie des Orerais de Fer Magnétique de Mokta el Hadid in French) in 1951. The mine is currently closed (Raddi et *al*., 2011b).

2.4. Tiouit Mine

Tiouit, located in the eastern Saghro Mountains, is a gold deposit with subhorizontal mineralized veins in a potassic granodiorite of the Upper Neoproterozoic. The deposit has copper porphyry and mesothermal systems. Gold was discovered in 1946-1947 in the Jemâa N'Ougoulzi sector, and exploitation occurred in three periods. Between 1950 and 1959, COMANSOUR company (Compagnie Minière de Jbel Mansour in French) was in operation, but ceasing activities after extracting 68,501 tons of ore. From 1959 to 1963, a Canadian company took over. Then from 1982 to 1996, SODECAT company reactivated the mine. The grades obtained were 7g/t Au and 57 g/t Ag with 0.4% Cu (Alansari, 2011).

2.5. Bouskour Copper and Silver Mine

The Bouskour copper deposit, located in the Saghro massif, is a vein type with resources exceeding 53 million tons at 0.8% Cu and 9 g/t Ag. It is associated with the late Pan-African tectono-magmatic system and has potential to place it among the world-class copper deposits. The first work in the deposit dates back to 1942 and was continued by various organizations. The mine was put into operation in 1958 with a production exceeding 10,000 t/year of metal. However, mining was abandoned in 1977 due to poor ore quality and the collapse of metal prices on the international market. Since 2008, Reminex company, a subsidiary of MANAGEM company, has undertaken large-scale exploration work, including geophysical studies and over 70,000 m of core drilling, resulting in the discovery of over 53 million tons of resources. The mine is currently closed (Maacha et *al*., 2011).

2.6. Oumjrane Mine

The Oumjrane deposit is located in the eastern part of the Eastern Anti-Atlas, approximately 124 km from Nkob following the road linking Ouarzazate Agadir-Tazarine, approximately 70 km (as the crow flies) north of Zagora, on the road linking Ouarzazate, Agdz and Errachidia, and 50 km (as the crow flies) from Alnif (Wafik et *al*., 2017). This deposit hosts various types of mineralizations: (1) a Cu-Ni vein-type mineralization in the district's southwest, represented by three veins: Bounhas, Afilou N'Khou, and Oumjrane Nord; (2) a Cu-Ni-Pb-Zn vein-type mineralization in the district's central region, primarily identified by the Riche Merzoug and Gara Tibert veins; and (3) a Pb-Zn and barite mineralization predominantly found in the district's northeastern extremity (Kharis et *al*., 2023). The moderate metal content in certain groups led to their abandonment.

2.7. The Tachilla Oolithic Iron Mine

The Tachilla oolitic iron deposit, located at the Youssef Ben Tachfine dam, is a part of a set of oolitic iron deposits in Morocco, known from the Meseta to the Anti-Atlas and dated to the Llandeilian (Middle Ordivicien), it is part of NNE-SSW syncline lying on the western flank of the Precambrian Kerdous massif. The ferruginous oolitic level appears in the upper part of the basal unit of the Tachilla Formation, attributed to Llanvirn (Middle Ordivicien). The Tachilla formation is a siliciclastic series of about 1200 m in thickness, formed by alternating sandstone beds and sandstone and micaceous schist beds. The deposit, which has reserves of over 10 million tons, was exploited in the 80s to supply iron to the Agadir Cement Plant company, currently is closed (Ettayfi et *al*., 2011) .

2.8. The Jbel Irhoud barite Mine

The Jbel Irhoud mine, located at 120 kilometers west-northwest of Marrakech and 66 kilometers southeast of Safi. The mineralization is found in a limestone layer of the Lower Cambrian, with the majority of reserves consisting of karst mineralization. The mine has historically been a significant supplier of Moroccan barite. It was initially operated by the companies Beaujean and Minindus, but ceased operations in 1952. In 1955, Moroccan Barytes Company was established, which eventually shut down in 1957. In 1958, the estate was rented to SMMPC, which expanded exploitation by acquiring additional quarries.

Since 1992, Moroccan Cements Company has started extracting limestone for cement production. Currently, the mine is closed (Wafik et *al*., 2011).

2.9. The The Roc Blanc and Kettara pyrrhotite Mines.

The Roc Blanc deposit, located at 20 kilometers north of Marrakech, has been extensively studied for its ore deposits. The deposit is a vein-like formation in Upper Visean-Namurian schist-sandstone rocks, containing iron-arsenic sulfides, sulfosalts, and copper parageneses. It is formed through the movement of aqueous fluids under mesothermal and epithermal conditions. In 1925, F. Busset surveyed the polymetallic field, which was later transferred to Bramram Mining Company (SMB). The Rehamna Mining Company (SMR) discovered five silver-mineralized veins with promising silver-lead-zinc contents. The BRPM company obtained the Roc Blanc permit and conducted mining operations, estimating reserves of 191,550 metric tons. The mine is currently non-operational due to silver price declines (Essarraj, 2011).

The Kettara deposit, located 32 kilometers north of Marrakech and 120 kilometers from Safi, was the first discovery of a sulphide mass in the Jebilet massif. The deposit has been developed through three phases: from 1938 to 1963, focusing on the gossan layer for iron oxide and high-quality ochre; from 1955 to 1966, pyrite was extracted for sulfur content, used in sulphuric acid production; and from 1964 to 1982, pyrrhotite was extracted for sulphuric acid production (Essaifi, 2011; Hakkou et *al*., 2008). The mine closed in 1982 due to storage challenges, low sulfur content, and ash waste accumulation (Essaifi, 2011).

2.10. Azegour Mine

The Azegour Cu-Mo-W Metasomatic deposit in Morocco, located at 65 kilometers southwest of Marrakech, was initiated in 1920 by Beni-Aicha and Entifa mining companies. The mine was later ceded to the Falta Mining Company in 1930. Between 1930 and 1946, molybdenum was extracted from the mines, with an average daily production of 200 metric tons. However, the mine shifted focus to copper deposits due to reduced reserves. From 1941 to 1971, 535,000 tons of copper were extracted, resulting in 28,000 tons of concentrate. Tungsten was discovered in 1950, but processing efforts were unsuccessful. The mine was permanently shut down in 1971 (Ibouh et *al*., 2011b).

2.11. The El Karit Mine

El Karit deposit, located northeast of Oulmès granite, is a quartz vein deposit containing cassiterite-beryl in the andalusite micaschists of the aureole surrounding Oulmès' hyperaluminous granite. Be-Sn mineralization occurred after quartz vein creation and tourmalinization, influenced by mesothermal hydrothermal circulations. It was once a significant tin deposit, dating back to the 17th century. Semi-artisanal mining began in 1925 and continued until 1973, producing 750 tons of concentrate with a 65% tin content. The cessation of mining in 1974 was due to disagreements over agricultural land. In 1998, the BRPM reassessed operations and Kasbah Resources obtained full ownership (Boushaba, 2011).

2.12. The Ait Ammar Mine

The Aït Ammar oolitic iron ore deposit is located 25 kilometers north of Oued Zem. The deposit was first discovered in 1919. Geological and metallogenic studies were conducted, and the subterranean deposits were estimated to contain 15 million tons of iron located in the Lower-Middle Ordovician of the Zaërs anticlinorium and were extracted in 1937. The mine accounted for one-third of the country's total production in 1952. It has been closed since 1963 (Boushaba and MICHARD, 2011; Nouri and Haddioui, 2016a, 2016b).

2.13. The Tansrift Mine

The Copper deposit of the Tansrift deposit in Azilal province was discovered during a copper research campaign in 1968-1972 and classified as a "redbeds" type. It was operated by SMEMIC in 1970 and successfully extracted and transported 650,000 tons of ore with a copper content of 1.5% over four years. The mine's closure in 1978 was due to its unfavorable geological configuration, including vertical benches, low strength, and thick clay layers (Barakat et *al*., 2022; Ibouh et *al*., 2011a).

2.14. The Aouli Mine

Aouli is one of three mines in the Upper Moulouya basin, located at 25 km northeast of Midelt. It's the oldest one to have been exploited (1926–1985), comprises a network of veins hosted within metamorphic schists and granites, with smaller veins also present in the Triassic sedimentary cover. The primary ore mineral in this area is galena, commonly associated with barite and fluorite (CaF_2) within a quartz gangue (Iavazzo et *al*., 2012). The mine was highly productive in the 1970s, and it's currently closed (Raddi et *al*., 2011c).

2.15. The Mibladen Mine

The Mibladen is the second mine of the Upper Moulouya basin mining area situated on a plateau primarily composed of Mesozoic carbonates overlaying the basement rock, was exploited between (1936–1985) (Iavazzo et *al*., 2012). Lead mine at Mibladen is a stratiform MVT type, located in Paleozoic schists, quartzites, marl-limestone layers, and Triassic red sandstones, influenced by the Hight-Moulouya Jurassic boundary (Raddi et *al*., 2011c).

2.16. The Zeida Mine

The Zeida mine is the third mine of the Haute-Moulouya lead district, the mineralization occurs as stratabound levels in the sub-horizontal Triassic arkosic sandstones, unconformably covering the granite basement (Iavazzo et *al*., 2012). The mines began operations in 1939 and were highly productive between 1972 and 1985, and the exploited orebody consisted mainly of cerussite with a rate of 70% of Pb and galena (Hachimi et *al*., 2014; Iavazzo et *al*., 2012; Raddi et *al*., 2011c). Of note, the three mentioned mines (Aouli-Mibladen-Zeida) have been permanently shut down due to mining waste contaminating aquifers and Moulouya River waters with lead and arsenic (Hachimi et *al*., 2014; Raddi et *al*., 2011c).

2.17. The Touissit-Sidi-Boubker Mine

The Touissit-Boubker Pb-Zn district, located on the Algeria-Morocco border, is a MVT deposit in dolomites, estimated to be of Aalenian-Bajocian age. The formation of these deposits is still debated, with proposed ages ranging from the Upper Jurassic to the Neogene era (Bouabdellah, 2011; Oubohssaine et *al*., 2022). The mine was operated by the Touissit Mining Company (Compagnie Minière de Touissit in French); The cumulative production of ore has reached 70 million tons, with an average grade of 4% Pb, 3.5% Zn, less than 1% Cu, and 120 g/t Ag. Then, it has been closed since 2002 due to depletion of ore reserves. Despite this, artisanal activities continue, producing 50 to 100 tons of lead scheids annually (Bouabdellah et *al*., 2012).

2.18. The Jerada Coal Mine

The Jerada anthracite mine, located at 60 kilometers southwest of Oujda, was discovered in 1927. The mine was established by the Sherifian Coal Company of Djérada (Société Chérifienne des Charbonnages de Djérada in French) in 1930 and began industrial exploitation in 1936. However, the global coal crisis in Morocco limited the mine's sales. The Moroccan government supported the mining industry, and a thermal power station was developed in 1967. The company, was known as " Coal mines of Morocco " (CDM), faced challenges in the 1990s due to inadequate layers, safety, cost, and debt repayment. The mine was declared bankrupt in 2001 (Chellai et *al*., 2011).

2.19. The Beni-Bou-Ifrour-Ouixane Mines

The Ouixane (Ouichane) iron district located near the Beni-Bou-Ifrour Mountain, has iron reserves estimated to be around 46 million metric tons. The district, which covers 36 km^2, includes multiple deposits with varying levels of economic significance. Between 1915 and 1951, the mines produced around 24 million metric tons of iron ore. In 1967, the Moroccan government established the SEFERIF company (Société d'Exploitation des Mines du Rif in French) to regain control of the reserves. The revised reserve estimations show a total of 26.4 million metric tons of iron ore, with an average iron content of 37.5% and a sulphur concentration of 4% (Bouabdellah et *al*., 2011; Moubchir et *al*., 2023). This mine is located in a geological environment characterized by skarns-type ferruginous deposits. These deposits are found in dolomitic and sandstone schists, along with Upper Jurassic-Cretaceous limestones. Mineralization occurs through pyrometasomatic replacement, resulting in complex calc-silicate mineral parageneses. A boiling fluid is responsible for high-temperature ferruginous mineralization, forming iron-rich and sulphide minerals (Bouabdellah et *al*., 2011).

3. Environmental and Health Impacts of MTE Generated by Abandoned Mine Lands in Morocco

3.1. Potential impacts on human health

The review of the selected articles did not identify any scientific studies explicitly quantifying the impact of MTE on human health. Nevertheless, some studies have attempted to explore potential associations between heavy metal pollution and human health by utilizing estimates derived from pollution indices. For instance, Nouri et Haddioui (2016b) evaluated the Human and animal health risk assessment of metal (specifically on Cd and Pb) contamination from Ait Ammar abandoned iron mine, using the animals' acceptable daily intake (ADI) index, which combines Daily intake (DI) of animals and $[Metal]_{animal-organ}$, in view of food safety and animal health standards; This research revealed that cadmium levels in animal organs beyond permissible thresholds, indicating potential health hazards linked to the consumption of tainted meat. In another abandoned iron mine, Moubchir et *al*. (2023) applied the Heavy Metal Pollution Index (HPI) and identified significant contamination in well water, which is utilized by 97.3% of local households. This contamination poses potential long-term human health risks to the community. In Tansrift mine, Barakat et *al*. (2022) evaluated the potential health risk by MTE, including non-carcinogenic effects on adults and children, using a health risk quotient (*HQ*) and the total hazard index (*HI*). This study identified non-carcinogenic risk for the adult population, whereas, for children, some samples showed *HI* values exceeding 1, indicating that the non-carcinogenic risk of MTE in the study area could be neglected for adults, but it could not be ignored for children's health. Another example, a search conducted on the Zeida site by Nassiri et *al*. (2021), examined the MTE contamination in the soil surrounding the mine, emphasizing human health risk evaluations using hazard quotients (*HQ*) and hazard indices (*HI*) for exposure paths including ingestion, cutaneous contact, and inhalation. As a result: As, Co, Mn, and Pb were recognized as significant health hazards, especially via ingestion for children exposed to arsenic. These findings emphasize the potential for significant health consequences from prolonged soil exposure and reinforce the necessity for focused efforts to mitigate MTE exposure in the Zeïda region.

These studies highlight the potential health risks posed by abandoned mines in Morocco. The cumulative findings emphasize the urgent need for scientific research that explicitly quantifies the impact of MTE on human health in areas surrounding abandoned mines. They also underscore the importance of implementing regulatory interventions and pollution control measures to protect public health from chronic exposure to hazardous metals commonly found in regions affected by historical mining activities.

3.2. Impacts on soil

Discharges from mining activities represent a significant source of soil pollution across the following regions:

- Assif El Mal : Khalil et *al*. (2013) analyzed metal contamination levels in soil and water from the abandoned mining district, identifying elevated concentrations of Pb, Zn, Cu, Fe, and Al. The study emphasized that metals in the mobile, exchangeable fraction are particularly toxic, posing a significant risk to soil ecosystems. This risk is most pronounced for Pb, Zn, and Fe, which are highly bioavailable and can be readily absorbed by plants and other organisms.
- Ait Ammar: Two studies conducted by Nouri et *al*. (2016 a, 2016b) evaluated the ecological risks posed by metals such as Cd, Pb, and Cu, using various indices and revealed considerable pollution, predominantly from anthropogenic sources, with Cd and Pb ranking highest in ecological risk. In the same region, Madani et *al*. (2015) further investigated the effects of soil toxicity on soil organisms, revealing that Cd and Cu, especially under acidic conditions, significantly reduced the reproduction of specific soil fauna.
- Bir Nehass: Research by Midhat et *al*. (2023) identified severe soil contamination from Cu, Zn, Pb, and Cd with concentrations exceeding typical background levels.
- Sidi Bou-Othmane : Barkouch et *al*. (2016) analyzed the mobility of heavy metals in mine tailings, reporting that Cd and Cu are particularly prone to leaching into surrounding soils. This poses risks for bioavailability and food chain contamination. Although Pb and Zn were found in more stable fractions, they still present long-term contamination risks, as environmental changes could mobilize these metals.
- Tansrift: Barakat et *al*. (2022) studied soil contamination around the abandoned using pollution indices revealed

considerable ecological risk, particularly from Cd and Cu, which primarily originate from mining activities.

- Zeïda: Extensive studies of the Zeïda site, a former significant lead reserve, consistently highlight severe soil contamination. Nassiri et *al*. (2021) and Ech-Charef et *al*. (2023) reported exceptionally high levels of Pb, As, and Cd, with contamination spreading to nearby agricultural soils via wind and water transport. Sequential extraction analyses by Nassiri et *al*. (2022) demonstrated high mobility for Pb, Zn, and Cd, indicating persistent contamination risks, particularly from tailings. Finally, Hachimi et *al*. (2014) established significant contamination even in areas distant from the mine, and El Azhari et *al*. (2016) reported arsenic concentrations exceeding 38,300 µg/L in soils near abandoned Zeida mine and in the Moulouya River and its tributaries.

These studies underscore the widespread and severe impact of abandoned mines on soil ecosystems across Morocco. They highlight the urgent need for targeted remediation and rehabilitation measures to mitigate metal contamination and safeguard ecological health in these regions. The rehabilitation of abandoned mine sites requires a thorough understanding of contaminated soil properties and composition (Nouri and Haddioui, 2016a), especially with acid mine drainage (AMD) which increases soil acidity and degrades visually landscapes due to the characteristic reddish-brown precipitates associated with it.

3.3. Impacts on onshore ecosystem

The primary waste materials of utmost significance in mining regions include cyanide, AMD, and particularly MTE. These components are not capable of being broken down by natural processes. They can remain in the environment for a long time, posing a risk to plants because they are sensitive to changes in their surroundings (Hakkou et *al*., 2008) . MTE have a detrimental impact on the life cycle of plants, particularly during the periods of seed germination and early development (Plante et *al*., 2011; Zitka et *al*., 2013); Also, they hurt plant growth by altering their physiological, biochemical, and metabolic processes, ultimately resulting in plant death (Oubohssaine et *al*., 2022). Iron and zinc are essential trace elements for animal and plant growth, but their toxicity occurs when their concentrations exceed metabolic requirements; for example it reduces photosynthesis in plants (Zitka et *al*., 2013). Nonetheless, some non-essential MTE like Cd have been found to hinder the germination process of various plant species, even at low concentrations; They also restrict the growth of roots of *Triticum aestivum* and *Phaseolus vulgaris* at levels above 500 mg/L (El Rasafi et *al*., 2021), as well as of *Thespesia populneoide*s, *Leucaena leucocephala*, and *Delonex regia* at 125 ppm (Sarwat et *al*., 2013). However a study conducted by Midhat et *al*. (2019) highlighted the presence of native metallophyte plants with high metal accumulation potential, offering insights into possible phytoremediation approaches.

3.4. Impacts on aquatic ecosystem

Research on the impact of abandoned mines on aquatic ecosystems in Morocco underscores the severe contamination of groundwater, surface water, and sediments with trace metals, posing significant risks to ecosystem health. In the Ouichane region, Moubchir et *al*. (2023) assessed groundwater quality near an abandoned iron mine, noting elevated mineralization and MTE levels attributed to mining activities. Similarly, in the M'fis mine region, Abdellaoui et *al*. (2023) studied groundwater around tailings. They noted low levels due to a carbonate geology and low water circulation, which limit metal dissolution and infiltration in this arid area. Diani et *al*. (2021) examined the High Ziz basin in surface waters, finding that Pb, Zn, Cu, and Fe concentrations were significantly higher than critical pollution thresholds. Pollution indices like the Heavy Metal Pollution Index (HPI) indicate critical contamination levels, with the clustering analysis linking these elevated levels directly to proximity to abandoned mine lands. The impact on surface water quality presents acute toxicity risks to aquatic organisms, highlighting the need for sustained monitoring efforts to safeguard these environments from prolonged metal exposure.

Bouzekri et *al*. (2019, 2020a, 2020b) and El Azhari et *al*. (2016) investigated the water and sediment pollution in the Moulouya River and its tributaries, near abandoned mines, identifying high levels of Pb and As. Pollution indices, including the geo-accumulation index (Igeo), confirmed severe contamination, with lead levels especially concerning near former mining activities. Aziz et *al*. (2014) further examined metal transport in the Assif El Mal River near an abandoned mining site; they also found that sediment toxicity was linked to the high mobility of metals in exchangeable and acid-soluble fractions, with Fe and Pb posing significant toxicity risks.

These metals' presence in sediment layers indicates a prolonged ecological impact, as contaminants are likely to leach into aquatic ecosystems over time. MTE accumulate in sediments, marine algae, and macrophytes downstream of mining areas and progressively pollute aquatic populations. Undoubtedly, these highly acidic waters with a high concentration of pollutants flow into surface water (such as rivers or lakes) and groundwater, resulting in a decline in their overall quality (Förstner et *al*., 1981).

Overall, the studies underscore that abandoned mines across Morocco introduce persistent pollutants, particularly Pb, Cd, Zn, and As, into groundwater, surface water, and sediments. These contaminants, originating from mining sources, represent a pressing environmental threat to Moroccan's aquatic ecosystems. They require targeted remediation and regular monitoring to mitigate their impact on biodiversity and ecosystem health.

4. Abandoned mine land rehabilitation

The rehabilitation of abandoned mine lands requires a multidisciplinary approach to design and implement effective strategies. A process proposed by the MTEDD in its National Action Plan for the Valorization of Mining Waste (MTEDD, 2021) can be broadly structured into three main phases:

✓ **Initial State**: A preliminary environmental assessment is conducted to characterize the site's current condition, identify contaminants, and assess the nature and extent of environmental risks.

✓ **Risk Assessment and Prioritization**: This phase involves evaluating the potential hazards, prioritizing interventions based on ecological and human health risks, and establishing cleanup criteria for contaminants of concern.

✓ **Remediation and Restoration**: A recovery plan is developed to address soil, water, and sediment contamination through techniques such as waste treatment, soil remediation, and site reconfiguration. The process concludes with final verification and monitoring to ensure sustainable rehabilitation outcomes.

Figure 2 presents a concise overview of the procedures proposed by the PANVRM, with slight modifications, for addressing the rehabilitation and valorization of nine priority abandoned mining sites in Morocco (MTEDD, 2021) .

The most critical step is the remediation phase, for which several techniques are available to decontaminate soils and waters, including physicochemical, thermal, and biological treatments. To attain this objective and improve the quality of the soil, two different approaches can be employed: ex-situ and in-situ procedures (Midhat et *al*., 2019; MTEDD, 2021). Ex-situ remediation methods include the transportation of contaminated soil to a different site for treatment. However, in-situ treatments enable the breakdown or immobilization of contaminants at the specific location. Various factors, including the properties of the pollutants, the soil type, and the geological and hydrological features of the polluted area, influence the choice between these strategies. The selected approach must address pollution's origin, manage the consequences, and safeguard the vulnerable entities (MTEDD, 2021).

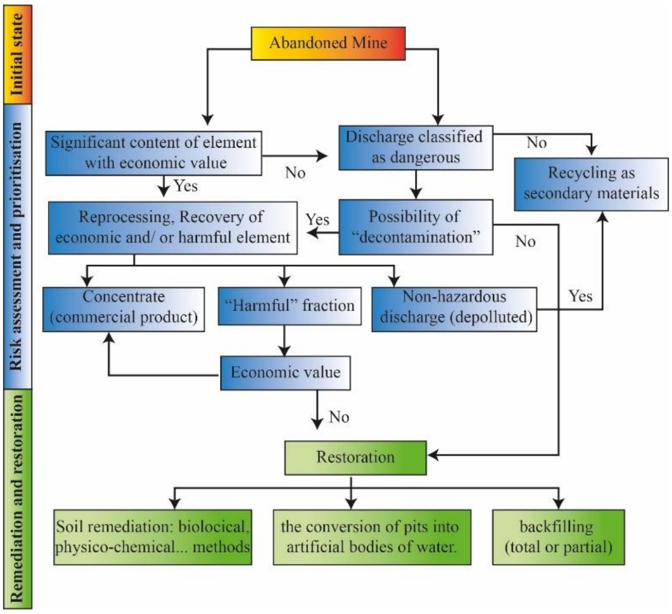

Figure 2: Abandoned mine reclamation plan proposed by the MTEDD (2021) with a slight modification.

4.1. Physicochemical approaches

The primary goal of mine site restoration is to mitigate the environmental damages resulting from the polluted area to an acceptable level. Lghoul et *al*. (2012) implemented a project to mitigate the environmental consequences caused by AMD from abandoned mining waste in Kettara by adopting two approaches: The first one involves the chemical stabilization of sulfur-rich mining waste, which is the source of AMD, using alkaline waste materials rich in limestone derived from phosphate extraction. The second approach seeks to reduce waste leaching by decreasing infiltration. According to this study, this concept involves the application of a layer of fine alkaline materials composed of limestone-rich waste (40% $CaCO_3$, 20% $MgCO_3$) over the abandoned mining waste. This carbonate layer restricts the infiltration of meteoric water by capillarity toward the sulfur-rich waste. An additional finer-grained layer further diverts this water toward drains installed at the bottom of the slope.

To prevent the environmental impact of AMD, strategies must be implemented to minimize its formation by regulating AMD production through preventive measures that target the oxidation of sulfide minerals, including:

-Sulfide Removal: Sulfides play a critical role in the formation of AMD. The removal of a substantial portion of these minerals from mine tailings, typically through processes such as flotation and gravimetric techniques, can significantly mitigate AMD generation. This method is particularly effective at active mining sites, although its application to abandoned mines may be limited due to restricted recycling options (Hakkou et *al*., 2008).

-Oxygen Inhibition: Since oxygen is a critical reactant in AMD production, preventing its access can mitigate the issue. Covers with low gas permeability or those that consume oxygen can be applied to mine tailings to limit oxygen availability. Materials used for these covers include water, soils, synthetic substances, and organic components (Goumih et *al*., 2022).

- Waterproof Covers and Water Ingress Control: Water is another crucial element in AMD generation. To minimize or prevent the formation of sulfuric acid, low-permeability barriers that block surface and groundwater infiltration can be constructed, using low-hydraulic conductivity soils or synthetic materials like geomembranes (Goumih et *al*., 2022).

-Storage, Diversion, and Release Covers (SDR): this method, used in arid or semi-arid regions, utilizes evapotranspiration to limit water infiltration into mine tailings and prevent AMD. These covers typically include a fine-grained layer over a coarser layer, with water retention properties adjusted to manage infiltration based on weather conditions. The effectiveness of SDR covers depends on factors like the thickness of the fine-grained layer, material properties, and external conditions such as rainfall and erosion (Wei et *al*., 2018).

By focusing on these preventive strategies, the environmental impact of AMD can be significantly reduced.

In the late 19th century, scientists proposed using biological techniques to remediate polluted areas as an alternative to physicochemical methods (Acharya, 1990). These biological approaches are cost-effective and environmentally friendly, involving microorganisms like bacteria, fungi, yeasts, and plants to detoxify pollutants. Some plants can even accumulate metals in their tissues (El Rasafi et *al*., 2021; Midhat et *al*., 2019).

4.2. Biological Methods

The main biological remediation strategies include bioventilation, bioleaching, bioreactors, composting, bioaugmentation, and biostimulation, bioremediation, biomining, phytoremediation. These two last techniques constitute the most often utilized in-situ and ex-situ methods.

Phytoremediation is the most popular studied method in Morocco, as plants are easily found in polluted sites. It involves using plants to remove or stabilize pollutants from soil, water, or air. Plants can accumulate toxic elements in their tissues, making this method particularly suitable for extensive environmental rehabilitation. In Moroccan's studies, various plants have been used for this purpose, such as *Eucalyptus globulus, Hirschfeldia incana, Citrullus vulgaris, Portulaca oleracea L., Stipa capensis Thunb., Lactuca vimina, Forsskaolea tenacissima L., Lycium intricatum Boiss.* and *Hammada scoparia* for their ability to accumulate metals like zinc, lead, copper, and chromium (El Rasafi et *al*., 2021; Midhat et *al*., 2019) or reduced the mobility and bioavailability of metals by immobilizing them in plant roots (Elouadihi et *al*., 2022).

The success of phytoremediation depends on factors like understanding the site's characteristics, selecting appropriate plant species, and considering the specific pollutants involved. Some of these plants are hyperaccumulator, can store large amounts of metals, resistant to the target metals, produce significant biomass, and grow rapidly even in contaminated environments (Midhat et *al*., 2019). While some plants exhibit strong phytoremediation potential, their use can be risky if the contaminants they absorb enter the food chain (Conesa et *al*., 2012).

Bioremediation is the process of employing living organisms, such as bacteria and fungi, to transform toxic contaminants into harmless substances. Various organisms, including bacteria, fungi, actinomycetes, and plants, have exhibited their capacity to remediate soil contaminated with diverse contaminants (Gallego et *al*., 2012). The primary objective of bioremediation is to rehabilitate contaminated sites to their original condition without inflicting additional damage to the ecosystem. Microorganisms can absorb, precipitate, oxidize, and reduce metals in the soil. For example, numerous mineral-oxidizing bacteria, commonly found in mines' sediments and soils, possess the ability to oxidize iron- and sulfur-containing minerals; such as sulfur-oxidizing *Acidithiobacillus thiooxidans*, and *Acidithiobacillus caldus*, as well as iron-oxidizing bacteria like *Acidithiobacillus ferrooxidans*, *Leptospirillum ferrooxidans* and *Leptospirillum ferriphilum* (Clark and Norris, 1996; Leduc and Ferroni, 1994; Nagpal et *al*., 1993; Korehi et *al*.,2013; Vardanyan et *al*., 2023). Several fungal species have demonstrated potential for use in biomining like *Penicillium simplicissimum* and *Aspergillus niger* can effectively mobilize metals (Brauer, 1990; Mulligan et *al*., 2004; Shah et *al*., 2022).

While biological remediation methods offer environmentally friendly alternatives to traditional physicochemical approaches, their effectiveness depends on the suitable microorganisms or plants present in appropriate locations under favorable conditions like soil composition, temperature, pH, and nutrient availability (Abatenh et *al*., 2017). Thus, these methods show promise, especially for large-scale remediation efforts, but also face challenges such as slow plant growth and the need for proper disposal of contaminated biomass.

4.3. Current Moroccan policies for regulation of mined land pollution

Mining legislation in Morocco based on the Dahir (royal decree) of 16 April 1951 does not include provisions requiring a mining title holder to take the necessary measures to address the consequences that may arise from its activity, and that could jeopardize public safety and health or harm the essential characteristics of the surrounding environment or compromise environmental conservation. However, since the Moroccan mining industry is transitioning, the public authorities have recently undertaken several reforms to promote the mining sector et (Lghoul, 2014).

Several legislative texts relating to environmental protection have been put into practice in this context. Thus, Law 28-00 on waste management and disposal obligates reducing waste at source, using biodegradable raw materials, and taking charge of products throughout the production and use chain (Lghoul, 2014). Environmental impact studies were established by Law 12-03, which set the objectives and content of any environmental impact study, namely, to assess in advance the possible repercussions, direct and indirect, temporary and permanent effects of the project on the environment (Lghoul, 2014). Law 12 May 2003 on the protection and development of the environment sets out the basic rules and general principles of national policy in environmental protection and development (Lghoul, 2014). Law 10-95 on water establishes a new institutional framework for managing and planning water resources (Lghoul, 2014). Even more, any deposit is subject to authorization issued by the Hydraulic Basin Agencies (ABH). Nevertheless, several mining sites have been abandoned without being rehabilitated and current regulations still do not require the operator to rehabilitate a site when mining ceases (Babi, 2012).

5. Conclusion

This study highlights the considerable environmental hazards associated with the pollution of abandoned mining sites, stressing the immediate necessity for efficient restoration measures. An essential concern is the failure to implement legislation restoring these sites, which intensifies ecological risks and prolongs the rehabilitation of affected regions. Moreover, specific mines, like those in the Ouichane region, continue to be perilously overlooked despite the dangers they present to the environment. The restoration plan has not been totaly executed, resulting in significant unresolved environmental problems.

This study highlights the considerable environmental hazards as efficient restoration, bolstered by enhanced enforcement of regulatory frameworks, is essential for alleviating these ecological impacts and fostering more sustainable mining activities in Morocco. It is advisable for relevant actors to promote scientific research, especially in bioremediation, due to its cost-effectiveness and substantial potential for environmental conservation. This significant topic will be explored in depth in a forthcoming essay, which will analyze the particular challenges and opportunities associated with rehabilitating high-risk mining sites.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data availability statement

Data will be available upon request from the corresponding author.

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Appendix

Appendix A: additional details for 19 identified AML without remediation

Name	Ore	Location, Geological Setting, Age and Type	Reference
1. Touroug- El Hamda	Fluorite, Barite	Eastern Anti-Atlas, GPS: 31°30'41.0"N 4°36'32.0"W, Transgressive Cambrian on Ougnat basement; Late to post-Hercynian	(Raddi et *al.*, 2011a)
2. Bou-Madine	Polymetallic with Ag, Au	Eastern Anti-Atlas GPS: 31°24'35.8"N 4°55'32.2"W, Post-Pan-African volcano-detrital series (PIII); Ediacaran (middle PIII)	(Abia et *al.*, 2011)
3. Imi n’Tourza	Oolitic iron	Eastern Anti-Atlas GPS: 31°13'52"N, 5°14' 20"W, Coverage of the Saharan platform; Lower Ordovician.	(Raddi et *al.*, 2011b)
4. Tiouit	Gold, copper, silver	Eastern Anti-Atlas GPS: 31°9'51.56"N, 5°47'29.02"W, Late Parafrican Potassic Granodiorite (PII-PIII); Ediacaran + Infracambrian.	(Alansari et *al.*, 2011)
5. Bouskour	Copper	Eastern Anti-Atlas GPS: 30°55'46.59"N, 6°18'4.86"W, Post-Pan-African volcano-detrital series (PIII); Ediacaran + Infracambrian.	(Maacha et *al.* 2011)
6. Oumjrane	Copper	Eastern Anti-Atlas GPS: 30°39'54"N; 5°07'29"W, Upper Ordovician (Quartzites of the 2nd Bani); Late-Hercynian hydrothermal	(Kharis et *al.*, 2011, 2023)

Appendix A: additional details for 19 identified AML without remediation

Name	Ore	Location, Geological Setting, Age and Type	Reference
7. J. Tachilla	Oolitic iron	Western Anti-Atlas, GPS: 29°51'8.71"N, W 9°29'9.60" , Transgressive Cambrian on the Ougnat basement; Late to post-Hercynian	(Ettayfi et *al*., 2011)
8. J. Irhoud	Barite	Located in the Hercynian massif of Jebilet, Western High Atlas, GPS: 31°52'30"N, 8°52'00"W, Veins and Karsts in the Lower and Middle Cambrian.	(Wafik et *al*., 2011)
9. Kettara and Roc Blanc	Sulfur, Ochre, Iron, Copper. Silver	Located in the Hercynian massif of Jebilet, Western High Atlas, GPS: 31°52'05.5"N 8°10'41.6"W, Devonian-Carboniferous Basin with tholeiitic magmatism. GPS: 31°47'28.2"N 8°00'09.9"W Veins in the folded Viseo-Namurian series, in the metamorphic aureoles of a granite	(Essaifi, 2011) (Essarraj, 2011)
10. Azegour	Copper, Tungsten, Molybdenum	Located in the northern flank of the Paleozoic Block of the Western High Atlas, GPS: 31°09'03.7"N 8°18'15.0"W, Skarns in contact with the Hercynian granite of Azegour	(Ibouh et *al*., 2011 b)
11. El Karit	Cassiterite	Central Plateau and Central Massif, GPS: 33°25'05" N, 6°06'09"W, Thermal aureole of the Oulmès granite. appears intrusive in the epimetamorphic terrains of the Cambro-Ordovician	(Boushaba, 2011)
12. Ait Ammar	Oolitic iron	Central Plateau and Central Massif, GPS: 33°04'02.2"N 6°39'15.1"W. Folded series of the SE of the Zaër. Lower-Middle Ordovician.	(Boushaba and Michard, 2011)
13. Tansrift	Copper	The Mines in the Central High Atlas, GPS: 32°12'05.8"N 6°18'03.3"W , Continental Lower Cretaceous Redbeds	(Ibouh et *al*., 2011a)
14. Aouli	Lead	High Moulouya - GPS (Aouli) :32°48'40.4"N 4°35'30.5"W, Veins	(Hachimi et *al*., 2014; Raddi, 2011c)
15. Mibladen	Lead	High Moulouya - GPS (Mibladen) : 32°45'03.5"N 4°39'56.1"W, MVT ;	(Hachimi et *al*., 2014)
16. Zeida	Lead	High Moulouya - GPS (Zaida) : 32°49'28.2"N 4°57'13.2"W, redbeds	(Laghlimi et *al*., 2015)
17. Touissit-sidi Boubker	Pb(Ag), Zn,Cu	Middle Atlas and Horsts Ranges. GPS : 34°28'33.1"N 1°45'48.5"W, Edge of the Jurassic threshold of the Hautes Plateaux, deformed into horsts and grabens; Jurassic MVT	(Bouabdellah, 2011)
18. Jerada	Anthracite	Horst Chain, Eastern Morocco, GPS: 34°18'13.3"N 2°11'47.6"W , Hercynian basin with Visian andesitic-rhyolitic magmatism	(Chellai et *al*., 2011)
19. Beni Bou Ifrour-Ouixane	Iron	Eastern Rif . GPS : 35°07'30.4"N 3°01'17.7"W, Skarns in the Jurassic-Cretaceous against subvolcanic diorites	(Bouabdellah et *al*. 2012; Moubchir et *al*. 2024)