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Thirty Years of Post-Mining Management in France: Lessons Learned and Long-Term Vision

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Abstract

On 4 October 1996, a major ground collapse occurred in a closed iron mine underlying the municipality of Auboué in eastern France, causing severe structural damages to numerous buildings. This event led to the urgent evacuation of approximately 150 families and marked the beginning of active and operational post-mining management in France, on legal, technical, scientific and social basis.

For nearly thirty years, the national authorities have implemented an operational strategy throughout the territory to both identify, classify and mitigate risks associated with thousands of former mining sites, including those presenting higher risks. In fact, actions have been prioritized over time to ensure an effective and systematic response.

During the first years, the primary focus was on managing subsidence and ground collapse risks in the iron mining basin of Lorraine, which affected more than 130 municipalities covering an underground mining area of 1,700 km². Subsequently, these efforts were extended to the entire country. As time progressed, additional types of hazards emerged, requiring the authorities to establish a hierarchy of risky sites, conduct expertise, and secure prioritised sites. These hazards included collapse of old shafts, gas emissions, water table rebound, pollution from waste deposits, mining water pollution and unauthorised intrusions into open mining structures.

Incidents and accidents have continued to occur, some of which were already expected while others were not. This constantly re-examines the way risks are anticipated and managed.

The accumulated experience across a wide range of sites and issues has enabled the French government, with a specific organisation and the support of around 150 dedicated professionals, to ensure the long-term management of post-mining challenges. Nowadays, special attention is given to the major potash, coal and iron mining basins, where phenomena such as rising water levels, ground collapses, and gas emissions remain evolving and require ongoing monitoring and intervention.

The authors provide a review of this experience-based feedback, as well as future perspectives for management in light of scientific and technical progress related to complex phenomena.

Keywords: Hazard, Risk, Environment, Mining, Post-Mining

1. Introduction

France was a major mining country for several centuries. Many substances were mined, as shown in the map in Figure 1. Mining operations gradually ceased as deposits were exhausted under economically viable conditions. Large-scale coal, iron and potash mining ceased definitively in the 1990s and 2000s. The only significant underground mine currently in operation, in metropolitan France, is a salt mine in the Grand-Est region.

Mining regulations had anticipated how to close mines safely with a process allowing mining operators to permanently relinquish their concessions. However, the technical requirements were not sufficiently stringent to guarantee the long-term safety of the sites and the protection of the environment. Environmental sensitivities and regulations in the 1960s were not the same as they are today.

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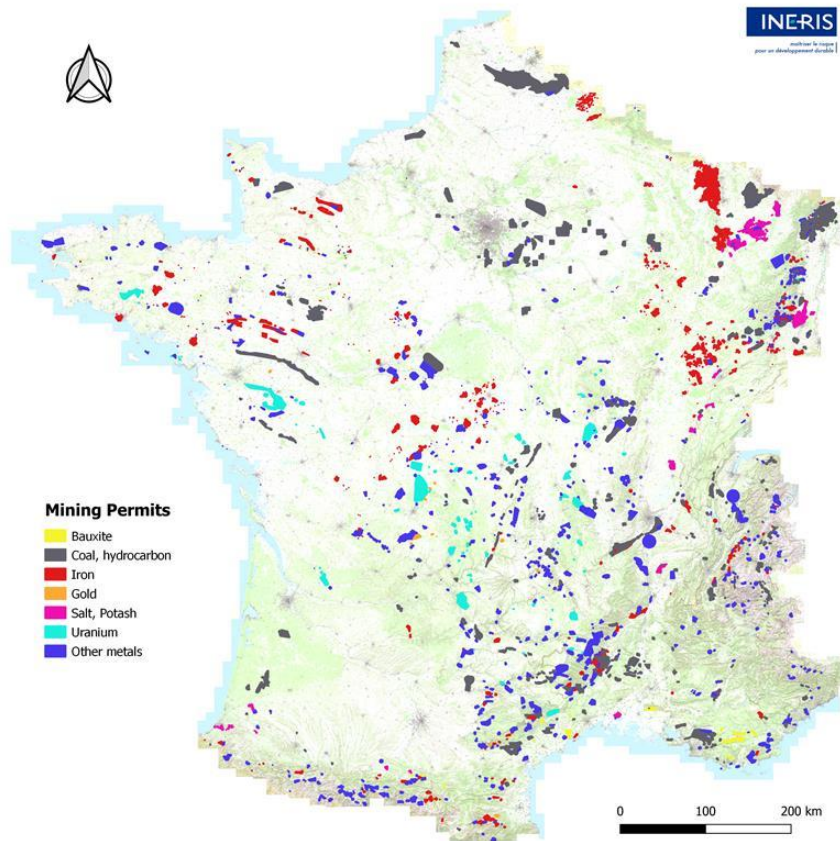


Figure 1 : Main locations of former mines in France (GEODERIS data)

When the first collapse occurred in 1996 in the Lorraine iron ore basin, causing significant damage to houses and threatening people's safety, the mining experts, the authorities and the public were taken by surprise. Emergency assessments identified the existence of numerous mining works directly above densely populated villages and towns. This triggering event led to the gradual organisation of a post-mining management system (Foucher et al, 2012) and the identification of all the problems likely to arise during closure (Didier, 2009).

In this article, we will present feedback on 30 years of post-mining management in France. We will present the experience gained in large mining basins (iron, coal, potash) and then in other mines.

2. Closure of Lorraine iron mines: the origin of post-mining in France

The Lorraine iron ore basin was mined for over a century until 1997. Over an area of 1,700 km², 3.1 billion tonnes of iron ore (1.2 billion m³) were extracted, leaving multiple cavities (including 40,000 km of mine galleries) wherever the mines were not deliberately collapsed, including under urbanised areas. Mining operations were carried out using the room-and-pillar method at shallow depths ranging from near-surface levels down to about 300 m, sometimes in multiple seams.

The problems that arose from 1996 onwards, particularly in the municipalities of Auboué (Figure 2), Moutiers, Roncourt and Moyeuve-Grande, led the French government to gradually take over from the mining operator by putting in place legal, financial and expertise resources with the aim of managing the post-mining period. This marked the beginning of post-mining management in France.



Figure 2 : (a) Damage caused by subsidence in Auboué (1996), (b) Collapse in Moyeuve (2012)

In order to carry out the necessary emergency assessments and enable local authorities to manage the risks, a team of experts was specifically commissioned to work on site. Then, in 2001, a team of experts was gathered within GEODERIS (a public interest group made up of the public bodies BRGM and INERIS), with a staff of more than 20 specialists and experts.

The assessments, which took into account past and more recent collapses (INERIS-a, 2002), (INERIS-b, 2002), made it possible to clearly distinguish between areas recognised as stable in the long term and those subject to a risk of ground movement. These areas are classified according to the type of expected hazards as follows:

- sudden collapse: sudden rupture, within a few minutes, of mine pillars, and geological overburden;
- sinkholes: sudden but localised appearance of a "funnel" resulting from the gradual collapse of the roof of a shallow mining cavity;
- gradual subsidence: large-scale vertical movement, which in some cases can cause significant damage to buildings, but which occurs gradually over several days or months and can be monitored effectively;
- residual movements: a hazard characterised by a residual ground settlement.

The analysis of these unstable areas has led to the production of a detailed hazard map (Figure 3). This map can then be used to make decisions regarding urban planning and monitoring. The nature of the monitoring depends on the nature of the movement and the vulnerability of the buildings on the surface. Thus, in the most sensitive subsidence areas, a microseismic monitoring system has been set up to detect the precursors of possible collapse, anticipate surface damage and protect people (Senfaute et al., 2000).

In urbanised areas at risk of sinkhole formation (Delaunay et al, 2025), extensive backfilling works have been carried out to restore ground stability and eliminate residual hazard. Some areas remain under periodic inspections.

Mine-induced ground movements studies were carried out in successive stages over a period of around 20 years, ranging from detailed analysis of archives to thorough crossed-analysis of mining works and geological setting of the overburden, whether favourable or not to a brutal major failure. Those focused on analysing the expected kinetics of mine induced subsidence in each area, assessing the rates of collapse from underground mine pillars up to the surface (Hosni and al, 2015), (Delaunay and al, 2021). Research is continuing, benefiting from developments in 3D numerical modelling with very high resolution of stress fields and failure mechanisms, as well as in the field of artificial intelligence to reanalyse data (more than 1,000 areas) and develop meta-models. The aim is to manage risks over the very long term, in a context where most ancient underground mines are inaccessible, precluding the possibility of acquiring further observational or investigative data.

In parallel with the management of ground movement risks, mine gas emissions were measured in the subsoil of several residential buildings close to a shallow gallery. This gas shows an strongly air enriched in CO₂ and depleted in O₂. This finding led to the development of a methodology for identifying areas likely to present risks and mapping "mine gas" hazards (INERIS, 2016). These areas are mainly located above mine openings and shallows voids (not flooded) where the configuration of the mine is conducive to gas migration

to the surface, particularly near homes. Extensive investigations are underway to understand the complex physico-chemical mechanisms and the gas intraseasonal flows involved before implementing long-term and costly mitigation solutions.

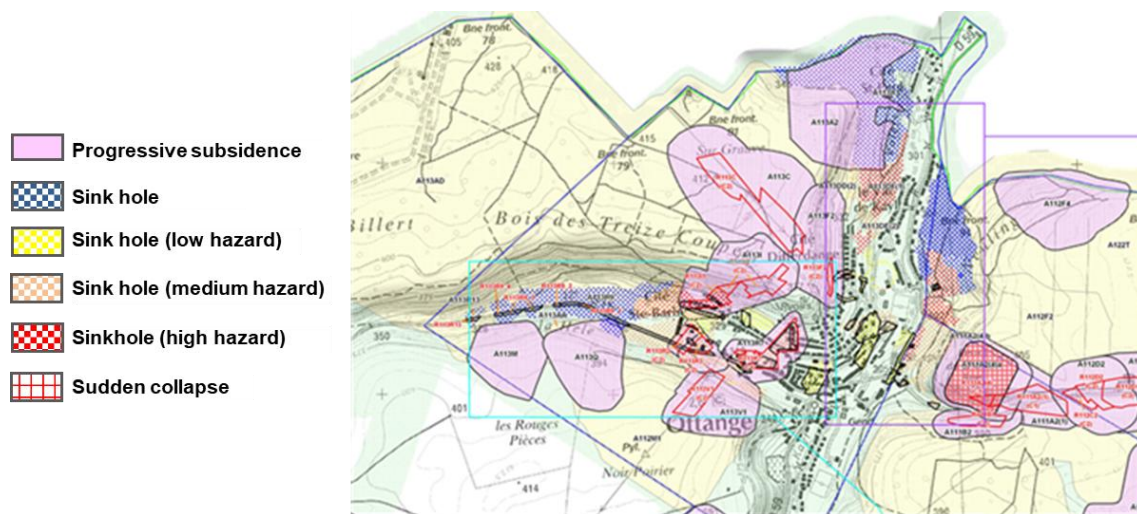


Figure 3 : Extract from the hazardous ground movement map for the town of Ottange (Source GEODERIS)

3. Closure of large coal mining basins: ongoing issues

After the Second World War, in 1946, all coal mining operations were consolidated into a single national company, Charbonnages de France, in charge of operating the five major coal basins to supply energy for the postwar reconstruction.

The Loire coalfield is located in the Saint-Étienne metropolitan area, underlying urbanised areas. It was mined industrially from the early 19th century until 1993, when the last discoveries (open-cast mines) were closed. During its operation, approximately 500 million tonnes of coal were extracted, mainly underground.

The Lorraine coalfield, located in the north of the Moselle department, extends on both sides of the French-German border. Although mining began in the Saarland part of Germany, the Lorraine coalfield only really developed from the mid-19th century onwards. Coal production, exclusively underground, took place in 58 pits sunk between 1818 and 1987. More than 800 million tonnes of coal were extracted until the mine closed definitely in 2004.

The Nord-Pas-de-Calais coalfield is the largest in France, covering an area of approximately 1,200 km² spread. It corresponds to the western part of a deposit that extends into Belgium. Intensively mined underground between the end of the 17th century and the end of the 20th century (1990) through a total of around 800 shafts, it is generally estimated that 2 billion tonnes of coal were extracted there.

Also the Gard coalfield, known as the "Cévennes coalfield", was mined industrially between the end of the 18th century and 2001. The Provence coalfield, often referred to as the "Gardanne coalfield" exploited industrially from the 19th century until the beginning of the 21st century (2003), almost exclusively underground via some fifty shafts and more than 800 descenderies.

When the last mine closed, the government transferred operational management of the Charbonnages de France sites to the BRGM within a special department (DPSM), with around 100 dedicated staff. Numerous residual post-mining issues have been identified and are currently being managed.

Underground coal mining has progressively created subsidence basins in which runoff water accumulates. To mitigate flood risks, around sixty wastewater and stormwater lifting stations, as well as pumping stations, have been installed, with long-term operational management implemented across many territories.

In the Nord-Pas-de-Calais basin, these facilities ensure the protection of approximately 6,000 ha of flood-prone areas resulting from mining activity and require an annual energy consumption exceeding 5 million kWh (2024). Pumping systems and the development of mine water overflow points have also been implemented in certain basins to manage both flood and pollution risks. The collected water is subsequently treated before

being discharged into the natural environment (example shown in Figure 4) (Jacob and al., 2023; Battaglia-Brunet, 2023).



Figure 4 : Water pumping and treatment station in the Lorraine coal basin (source: BRGM/DPSM)

In Lorraine coal basins, the rise in water levels following the cessation of mining and closure was also problematic, with the risk of flooding many urbanized districts (Corbel et al, 2017). Extensive hydrogeological investigations and modelling were required to design an optimal network of pumping wells aimed at maintaining a low groundwater level, with an associated piezometric monitoring network to control the water rebound.

Mine gas is also a concern, with emissions occurring when water rises. Around 200 outlets are monitored, as well as some mine gas transport networks (Défossez et al, 2013), (Dheilly et al, 2017). Management of this residual risk has not been stabilised in the large Nord-Pas-de-Calais basin, as the rise in water levels is very slow and will continue for several decades.

It should be noted that for methane emissions, beyond the "safety" aspect managed to date, in 2024, European regulations (Regulation EU 2024/1787) on greenhouse gas emissions, Member States are expected to establish an inventory of methane emissions from former underground coal mining sites on their territory (Article 24 of Regulation EU 2024/1787). For each site concerned, the inventory lists the sources of so-called "point" emissions, mining shafts, ventilation shafts, unused ventilation ducts, and unused gas collection shafts, in the form of a direct measurement at source or a quantification, with a view to monitoring them if emissions exceed 0.5 tCH₄/year (INERIS, 2025). In this context, the government has undertaken significant methodological and inventory work to identify the sites that need to be equipped with instruments to meet regulatory requirements.

With regard to coal spoil heaps, an initial inventory identified approximately 2,100 coal spoil heaps (stripping products, fine wash residues, etc.). Some heaps present a risk of overheating and are monitored continuously.

As for ground movement, the problem is less acute for deep mining operations in large basins than for iron mines. There are still a few areas at risk of subsidence and collapse, as well as many areas in the Loire basin at risk of sinkholes. However, the risk of mine shaft head collapse in urbanised areas remains a concern. Around 2,000 mine shaft heads have been identified in the Loire basin and 800 in the Nord-Pas-de-Calais basin. The vast majority of these shafts are not marked on the ground. This poses a real risk to existing buildings, and collapses have occurred, causing damage to buildings. The challenge today is to prioritise these unmarked shafts and locate them using appropriate means. Numerous geophysical tests have been conducted and, despite technological advances, the results have not been satisfactory, mainly due to various interferences in urban areas. Research is continuing in order to find solutions.

4. Closure of the potash basin mines: an unsuccessful conversion

The industrial exploitation of the Alsace potash basin in eastern France began in 1910. In total, 570 million tons of ore were extracted through 11 mines and 24 shafts. The potassium chloride produced was mainly used in the manufacture of fertilizers. Resource depletion, technical difficulties, and international competition led to the gradual closure of the sites starting in the 1980s.

In 1999, the StocaMine site, located in a specific sector of the historic mine, was created to store hazardous waste in the former underground galleries. A total of 44 kt of waste was stored there. On September 10, 2002, an accidental fire started deep within the storage facility. Toxic fumes spread to the last active mining sector, causing the immediate and permanent shutdown of potash extraction in Alsace. Today, two shafts remained open. Some of the most hazardous wastes—depending on the scenarios studied—has been removed from the site, and closure operations are currently underway (Gombert et al., 2025). These operations involve installing watertight plugs in the access galleries and backfilling the voids around the remaining waste, in order to prevent water pollution in the future. The last two shafts will then be sealed to limit groundwater inflow as much as possible.

For nearly a century, the massive extraction of ore generated large quantities of saline residues, initially stored in spoil heaps before later being discharged as brine (Noyer et al, 2014). This historical management led to major saline pollution of the Alsatian aquifer, one of the largest freshwater reserves in Europe. To address this damage, remediation and monitoring strategies have been implemented, including pumping saline water from the affected aquifer and dissolving and sealing the former spoil heaps.

5. Risk management for former metal mines

5.1. Ground movements

Following the collapses in the iron basin, once the dedicated teams of experts had been set up as described above, the Ministry responsible for mines launched an operation to inventory mining hazards, specifically "ground movements", throughout the country.

After developing a methodology and compiling documentary information, fieldwork was undertaken at sites considered relevant. All sites were then ranked according to potential risk criteria in order of priority for study from P1 to P6. During the first 10 years, 171 sites with priority levels P1 to P3 were studied and detailed hazard maps were produced. Next, the 25 sites with priority level P4 were studied, and the 218 other sites with priority levels P5 and P6 are currently being studied.

Next, for each ground movement hazard zone, the hazard and surface issues are cross-referenced. All sites affected by potential risk zones are then analysed to confirm and assess the risk. The risk studies consist of determining the conditions of the mine voids in each zone and identification of surface assets. This is done by visual observation of the cavities when the site is accessible from below or by drilling from the surface. Laser measurements are used to examine and measure the cavities from the surface, and sonar measurements are used when water is present in the underground works.

Once the risk has been confirmed (presence of proven voids at shallow depths and surface assets), it is then assessed. If the risk is medium to high, risk management is recommended, either by eliminating the hazard by filling the mining voids or by eliminating the surface issues (expropriation of houses). If the risk is considered imminent, visual monitoring is generally put in place to assess the evolution of the deterioration of the mining cavity roof.

5.2. The issue of mining waste

As priority management of the issue of ground movements progressed, particularly in the iron ore basin, mining waste became a new concern, since teams began working on former polymetallic mining sites. After the initial emergency response and safety measures, a comprehensive and exhaustive inventory of all mining waste deposits (polymetallic mines) began in 2006, in accordance with the Mining Waste Directive (DDIE 2006/21/EC) (Baranger and al, 2016), (Chapon et al, 2023).

A comprehensive methodology was developed for this inventory and prioritisation process. Overall, it involves cross-referencing the parameters of each deposit (substances, sizes, etc.) with the surrounding assets

and uses (population and environment), based on a scoring method classifying sites into five main categories for "population-environment impact" (Table 1) and three categories for "stability".

Table 1: Mining waste sites – risk class characteristics

Class	Class characteristics
E	Area likely to pose a significant risk to the environment and human health, requiring urgent detailed environmental assessment if this has not already been carried out. Management measures are to be considered, the scope of which is to be refined following the environmental assessment.
D	Area likely to pose a significant risk to the environment and human health and requiring a detailed environmental study to assess the potential severity.
C+	Area likely to pose a risk to the environment without constituting a serious identified risk based on the available data. A screening study (C+: priority, C-: non-priority) is necessary to assess the potential level of risk and establish a reclassification to B (or A) or D (or E).
C-	
B	Area that does not pose a risk to the environment but, as some deposits may be close to residential areas, it is necessary to flag it as a hazard for long-term risk management.
A	Area posing no significant risk to the environment or human health. It does not require any particular monitoring or study.

The field inventory operation then mobilised several teams across the entire metropolitan territory for approximately two years. It identified more than 2,100 deposits, which were grouped into 233 homogenous sectors. Figure 5 shows the classification for these sectors.

Following this DDIE inventory and environmental classification, several types of studies are planned:

- Detailed environmental and health study / IEM: this type of study is based on one of the approaches developed as part of the national policy for the management of polluted sites and soils by the Ministry of the Environment. This approach is based in particular on the development of a conceptual model and on the Interpretation of the State of the Environment (IEM). These studies concern classes E and D;
- Environmental audit: a specific environmental study focused on a very specific issue and less comprehensive than an IEM study;
- Orientation study: this type of study concerns sectors with no known operator, pre-classified as C+ or C-. The purpose of this study is to collect information to supplement that already acquired as part of the DDIE inventory in order to decide on a possible reclassification of the sector.
- "House on deposits" study: this type of study is intended to assess the health risks to the occupants of one or more dwellings located on a former mining deposit;
- Stability assessment: simplified geotechnical diagnosis to assess the risk of instability of the deposits responsible for classifying an area as III (the most unfavourable classification in terms of geotechnical stability).

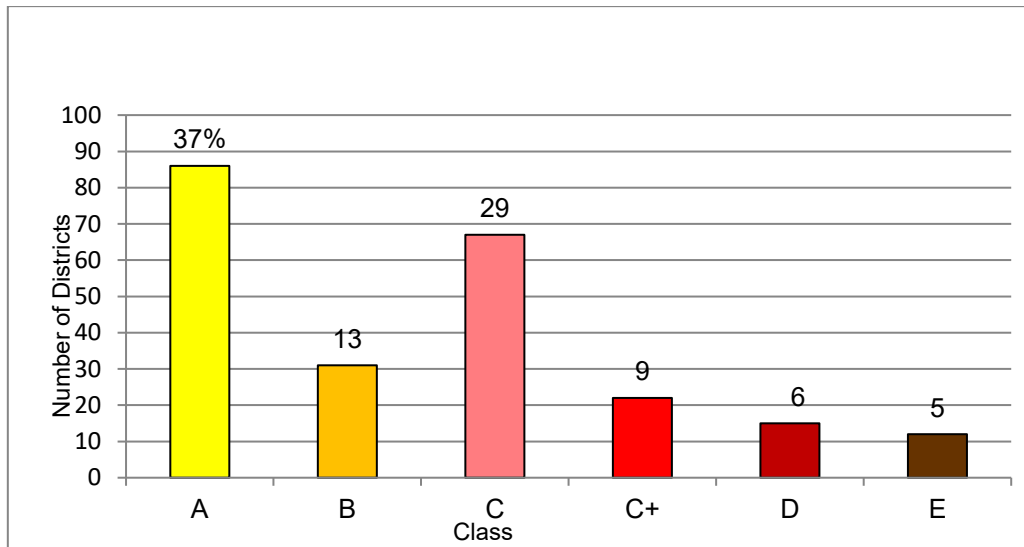


Figure 5 : Classification of the 233 sectors based on environmental and health criteria (Source: GEODERIS)

The completion of all priority studies took around ten years. Detailed environmental investigations were conducted to characterise the different environments, enabling health risks to be assessed. Exhaustive fieldwork led to the reclassification of Class C sites, with many sites in this class ultimately undergoing detailed IEM-type studies.

At certain priority sites that have an impact on the environment, safety measures are being implemented, in particular appropriate water management and treatment prior to discharge (Figure 6). Particular attention is being paid to taking into account intense rainfall events in order to prevent instability, erosion and the uncontrolled release of residues containing metals and contaminated water into the environment



Figure 6 : Management of the tailings dams at the former Salsigne gold mine

4. Conclusion

The management of post-mining consequences in France is handled by the State with the support of an effective operational and technical organisation in the field, which has proven its worth over the last 30 years (Lebot et al, 2026). Around 150 people are dedicated to this activity, with different skills, and a budget of around €30 million per year (reference 2025). The operational, scientific and technical feedback gathered over these 30 years clearly shows that we are facing a long-term global management issue. This management is also guided by the ongoing definition of priorities in line with the relatively substantial budgets allocated for this purpose.

Water collection, pumping stations and water treatment are systems that must inevitably be maintained in the long term. This represents a significant cost within the post-mining management system.

With regard to the issue of ground movement, future challenges will involve updating hazard maps following the ground movements that occur regularly in given areas. But it will also be necessary to anticipate recurring questions about areas with significant hazards where no major events (ground movement) have occurred. This is the case, for example, in the Lorraine iron basin, which has more than 1,000 sensitive areas covering approximately 130 municipalities. Scientific research, based on advances in numerical modelling, artificial intelligence and new knowledge in rock mechanics, is being conducted to help answer these questions.

Old open structures, shafts and galleries, estimated at more than 40,000 in France, present an insidious risk that is difficult to control given their number and nature. In 2007, there were two fatal accidents following rock falls during an intrusion into open galleries. Furthermore, securing these structures is hampered by environmental considerations, as the old galleries have provided a habitat for protected wildlife (mainly bats).

Gas emissions from old structures, as well as from cracks in the ground, are sometimes difficult to control, involving complex phenomena. In some closed coalfields, it can take several decades for the water to rise, and in such cases, the gas that rises through the voids remains difficult to control and requires constant monitoring.

The management of mining waste sites is under control following the comprehensive inventory that was carried out. Safety measures for the priority sites are being implemented over time, given the scale of the work required. Monitoring also contributes to better control and to feedback from experience.

Over the past three decades, post-mining management in France has led to significant advances in the understanding and control of the associated technical challenges. However, given the diversity of sites and the phenomena identified, unexpected problems and unpredictable events still occur. Sites are evolving (aging of structures, water movements, etc.), and site redevelopment, urbanization, and climate change are all factors that require continuous vigilance in the management of post-mining activities and the associated risks.

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Post-mining Sinkhole Hazard and Risk Management in France: Feedback and Outlook

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Abstract

France's long history of mining, with more than 4,000 mining permits, led to the development of a specific risk management policy in the late 1990s. To date, more than 250 risk assessment studies have been conducted to evaluate the impact of abandoned mines on infrastructure and land use planning. 80% of identified risk areas are affected by sinkholes, with over 4,000 cases reported and around ten new cases appearing each year. The assessment of the predisposition to sinkhole formation on former mining sites is based on expert judgement taking into account various criteria and data on previous sinkholes. Discussions have been underway to improve and modernise these methods in France. The European SIRIMA project focuses on the development of quantitative prediction tools, in particular probabilistic models and machine learning. A comprehensive database and a web map to document sinkholes in the project's partner countries: France, Germany and Poland. This work has revealed that it is difficult to complete all the data due to the age and loss of information. The information collected will be used to analyse the conditions under which sinkholes occur in order to better manage this risk in the future in coal-mining regions in transition, particularly in France.

Keywords: Post-mining, sinkhole, hazards, prediction, risk management, SIRIMA

1. Introduction

Like many other European countries, France has a long-held mining tradition. In French territory, the earliest evidence of underground mineral resource dates back to the Neolithic age. The exploitation continued over the centuries. These were small artisanal exploitations. However, it was the industrial revolution (17th - 18th centuries) that constituted the decisive impetus in the rise of French mining activity. It was the birth of the major mining basins.).

Mining activity continued to flourish in France during the first half of Twentieth century, mainly because of the two world wars. In the aftermath of the Second World War, the national effort undertaken for the reconstruction of the country and the reduction of French energy dependence facilitated the revival of mining activity. The production of coal and lignite increased rapidly to 60 million tons in 1958, a record year. Different economic factors, the development of use of hydrocarbons in energy production, competition from other countries and the depletion of certain deposits have gradually generated the decline of French mining activity. Initiated in the early 1960s for coal and iron and in the early 1980s for the exploitation of other substances, this decline has accelerated since the early 1990s. Coal exploitation stopped in 2004.

The French post-mining is a wide story; there were more than 4,000 "mining titles" in mainland France. Many substances were exploited: coal, iron, aluminum, uranium, salt, potash, gold, silver, and a lot of other metals. There are many coal mines throughout the territory, some of them are very old (Figure 1).

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At the end of the 1990s, a series of major ground movements (subsidence, sinkhole, massive collapse) occurred in the Lorraine iron ore basin, affecting safety for persons and property in some cases. After these events, France developed a mining risk management policy and implemented various tools to first make sure that the right expertise and research was in place, then followed that with operational tasks.

The first step was the adoption of the law of March the 30th 1999. The main points of the law are:

- Extension of the mining operator's liability in terms of time and space. This liability is taken over by the State at the end of the operation or upon the disappearance of the mining operator.
- Implementation of monitoring if mining risks persist and are not addressed.
- Creation of administrative tools to manage land use in mining areas exposed to risk: Mining Risk Prevention Plans (PPRM).
- Possibility for the State to expropriate property exposed to mining risk.

Currently, administrative and sovereign control is managed by the Ministry for the Ecological and Inclusive Transition and its Regional Division (DREAL). Mining expertise is carried out by an independent entity, GEODERIS, a French "Public Interest Group" between BRGM and Ineris. BRGM's Department of Prevention and Mine Safety is responsible for safety and operational management of facilities and safety equipment. Ineris and BRGM belong to the Scientific and technical network.

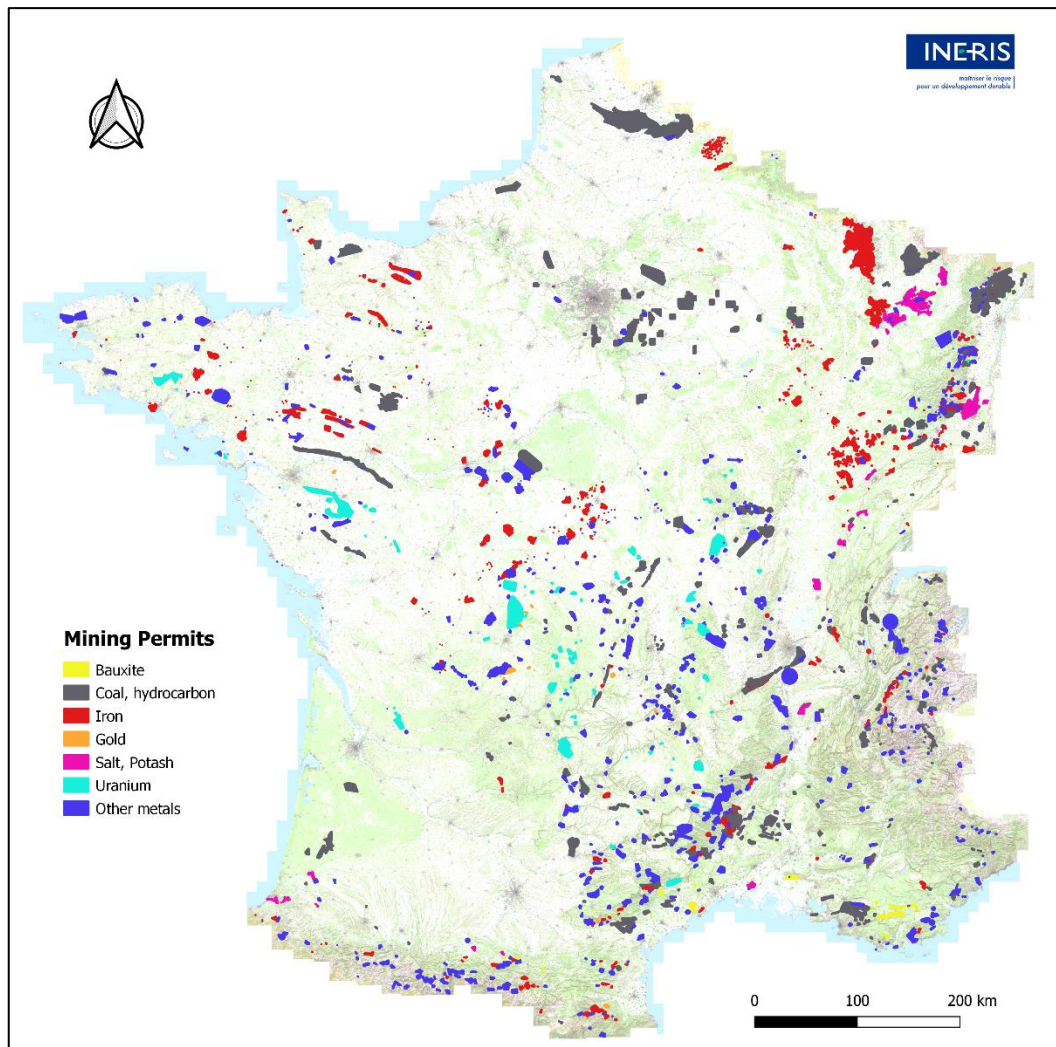


Figure 1: Location of Mines in France

In France, all old mines are being studied. The aim is for each phenomenon, to delimit areas where hazards exist and assess their level, in order to determine the risk for the existing stakes and the possibilities of construction or development in terms of land planning. Sinkholes are the most common type of ground movement phenomenon in France. A specific methodology for assessing hazards and risks has been developed (Delaunay and al, 2025).

2. Sinkhole: definition and hazard assessment

2.1. What is a sinkhole?

The sinkhole hazard is a frequent and dangerous phenomenon associated with shallow abandoned mines. Sinkhole (or pit hole, crown hole - sudden, localized collapses of the ground surface) are characterized by the sudden appearance on the surface of a collapse crater, which generally varies from a few meters to several tens of meters in diameter (Ineris, 2018; GEODERIS, 2019). The depth of the crater depends mainly on the depth and dimensions of the mining cavities that caused it. There are several mechanisms that cause sinkholes: breakdown of the roof of a gallery or mining cavity (Figure 2), collapse of broken isolated pillar (s), collapse of a shaft head (backfilled or empty). Two circumstances are likely to stop the phenomenon of sinkhole uplift affecting underground mining works:

- Stabilization of the underground void; this is particularly the case when there is a thick, unbroken layer of rock strength in the overburden.
- The void filling itself as the ground expands in the sinkhole rise chimney; the phenomenon will stop when the expanded volume of the chimney is equal to the volume available in the cavity and the chimney.

The development of sinkholes in the overburden is generally a slow process, which can take several years or decades. However, sinkholes appear suddenly on the surface, making them potentially dangerous for people and property located within their area of influence. Discontinuous deformations appear during, immediately after or very shortly after the exploitation of the seam, but sometimes a long time afterwards.

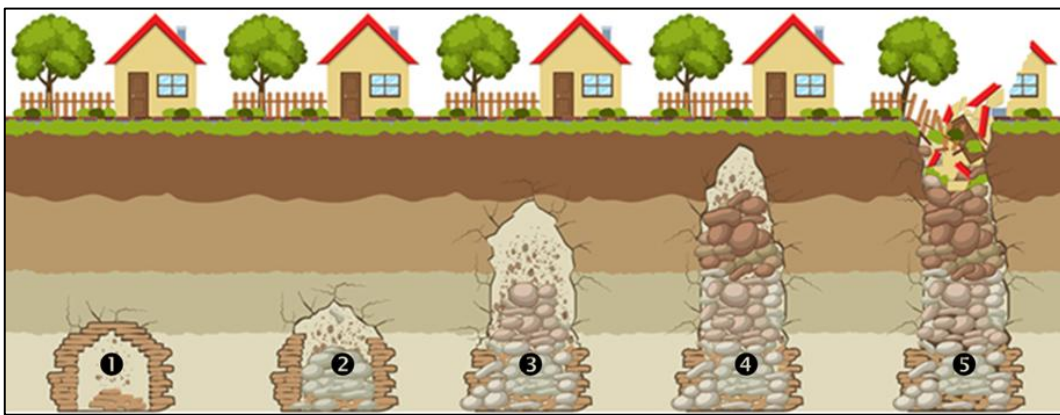


Figure 2: Mechanism of sinkhole formation (Source: GEODERIS) and progress stages (1 to 5)

2.2. Hazard assessment: methodology and limits

The concept of hazard used in the field of mining risk prevention in France is defined as the probability that a mining-related phenomenon will occur at a given site during a specific reference period, reaching a quantifiable or measurable intensity (Ineris, 2018). This characterisation is based on the systematic cross-referencing of two major components: the foreseeable intensity of the phenomenon and its probability of occurrence. In the post-mining context, the reference period spans several decades or even centuries, which means that the inevitable deterioration of old underground infrastructure must be included in the analysis.

The intensity of a phenomenon corresponds to the extent of the disruption, damage or nuisance likely to result from the feared event. It is based on measurable physical quantities. To assess this intensity, experts identify the most discriminating physical quantities, such as the maximum diameter of a sinkhole or the amplitude of horizontal ground deformations, in order to characterise the severity of the foreseeable consequences. Although the number of intensity classes may vary depending on the accuracy of the data, the standard nomenclature used in France generally comprises five levels ranging from very limited to very high, the latter being reserved for events of exceptional and devastating intensity. In the case of sinkhole hazard assessment, three intensity levels are used based on the diameter likely to form on the surface: limited (diameter < 5 m), moderate (5 m < diameter < 10 m) and high (diameter > 10 m).

Due to the complexity of the mechanisms involved, the heterogeneity of the natural environment and the often-partial nature of the information available on old mines, it is difficult to adopt a quantitative probabilistic

approach to assess the occurrence of phenomena (Ineris, 2018). Consequently, it has been decided to favour a qualitative approach based on the concept of predisposition, which reflects a site's intrinsic sensitivity to being affected by a particular disorder (GEODERIS, 2019). The analysis of this predisposition is based on feedback, examining whether similar phenomena have already occurred at the site or in similar geological and mining contexts. It also requires an in-depth examination of the type of work, the configuration of the operation and the hydrogeological environment. This approach to assessing predisposition can be complicated in some cases, particularly for older operations, due to the scarcity of available information. Predisposition classes are usually divided into three or four levels of sensitivity: very low sensitivity, low sensitivity, sensitivity and high sensitivity.

In the case of sinkholes caused by roof failure of the gallery, an additional step involves assessing the theoretical height of chimney collapse from which the phenomenon is blocked by self-bulking. Over several years, Ineris has developed an analytical model for predicting the height of sinkhole uplift that takes into account the operating pattern implemented in underground works (abandoned chambers and pillars, different types of galleries). This volumetric model assumes that the phenomenon is blocked by self-bulking resulting from the expansion of collapsed ground (Didier & Salmon, 2010).

Using information available on the geometry of the works and the properties of the ground forming the overburden, the model makes it possible to determine the predictable height of the chimney rise and thus to assess the risk of sinkholes appearing on the surface.

The final hazard level is obtained by cross-referencing intensity classes with predisposition classes within a matrix or cross-tabulation table (Table 1). This qualification principle allows qualitative values or mixed criteria to be combined to produce a hierarchy of three hazard classes: low, medium and high. This hazard level is assessed on a case-by-case basis for each site, allowing for adjustments to adapt to local specificities and the physical mechanisms specific to each feared phenomenon.

Table 1 : Mining hazard qualification

Intensity	Predisposition		
	Unlikely	Likely	Highly likely
Low	Low	Low	Medium
Moderate	Low	Medium	High
High	Medium	High	High

The final phase of the assessment consists of hazard mapping, which must cover all surface areas likely to be affected (Figure 3).

GEODERIS, with the assistance of Ineris and BRGM, has carried out approximately 250 risk assessment studies since 2001. Given the large number of former mining operations in France, priority was initially given to large mining basins and mines with numerous surface buildings. The results of this large investigation are 12 350 hectares of mapped hazards. In this context:

- The phenomenon of sinkholes is assessed across all sites studied.
- About 80% of the hazard areas are concerned by sinkholes.
- Almost 4000 sinkholes have been identified (through archives or directly observation on former mining sites), just under half of which are located on former coal mines (Figure 4).
- Between 5 to 15 sinkholes appear each year.

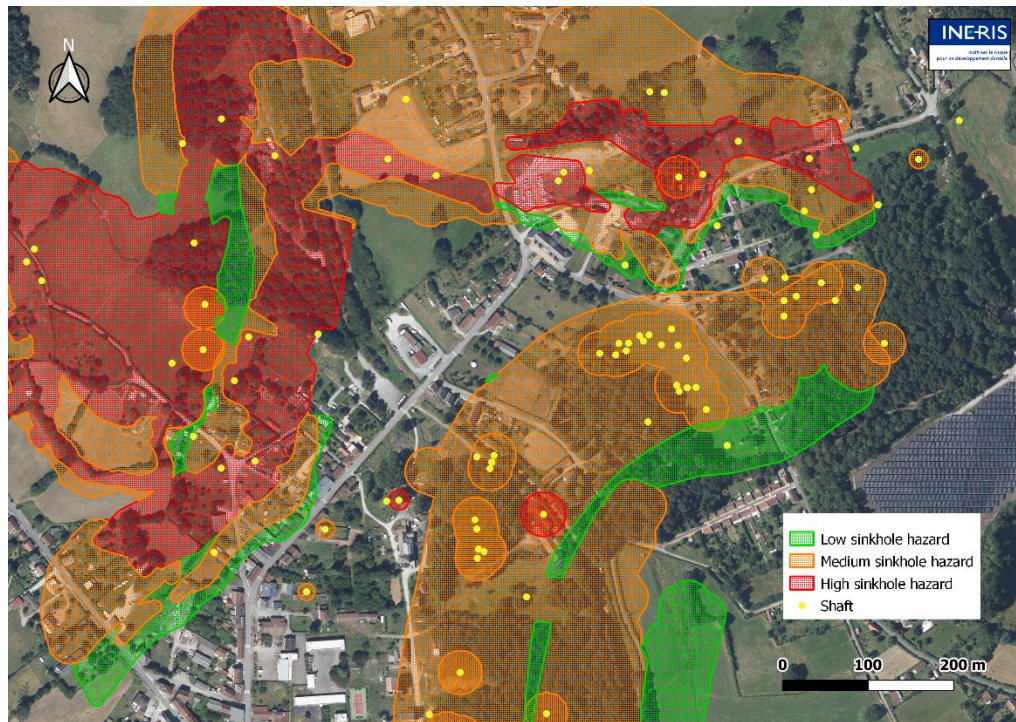


Figure 3: Extract from a sinkhole hazard map

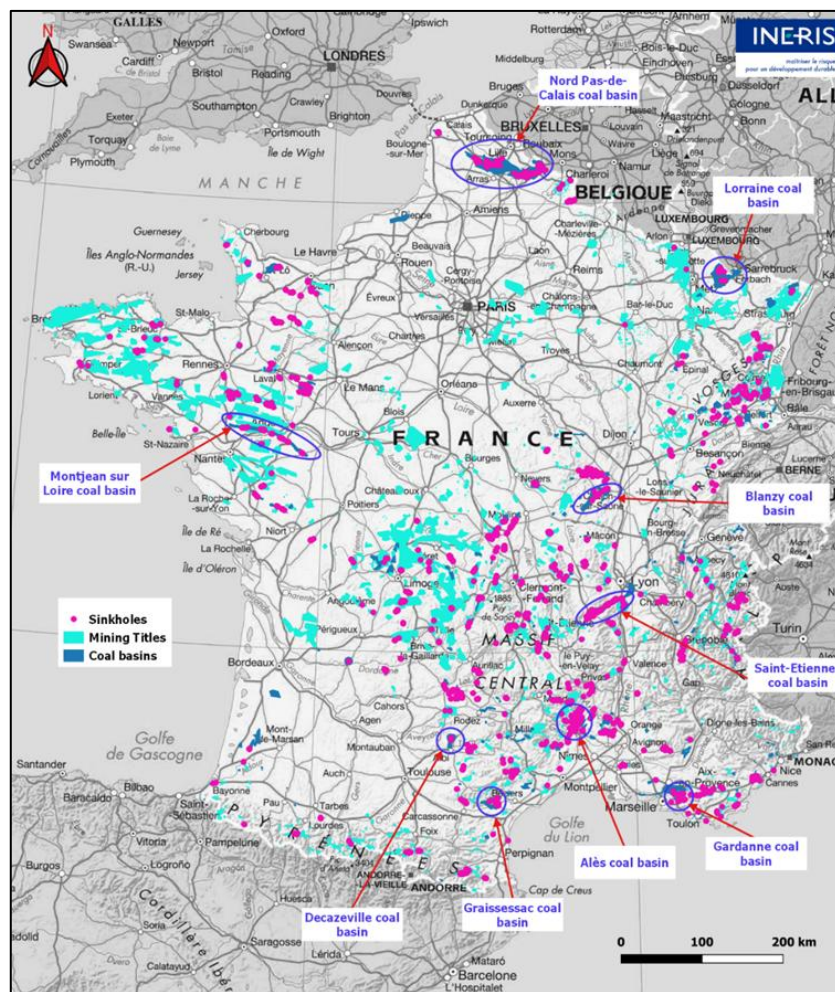


Figure 4: Map of the mining activities and sinkholes localization (Vuidart, 2025)

The approach implemented over several years is based on qualitative expert analysis, which is often hampered by a lack of data. Ineris has recently conducted several studies to improve assessment methodology, using quantitative approaches and modern tools:

- 2015-2017: new grid for estimating the intensity of sinkholes (Ineris 2015, 2018). From 2024: reflection to define quantitative approaches to estimate the predisposition of old mining sites to sinkhole phenomena. To carry out this study, Ineris is participating as a partner in the European SIRIMA project.

2. The SIRIMA Project

2.1. Presentation (Siwek and al, 2025)

The SIRIMA project (Sinkhole Hazard and Risk Management in Post-Mining Areas, risk management of sinkholes in post-mining areas) is co-funded by the European Union's Coal and Steel Research Fund under the RFCS-2023-01-RPJ Coal Research Projects action, grant agreement number 101157400. This project aims to deepen knowledge and experience regarding threats to post-mining areas in EU Member States. The main objective of the project is to reduce the frequency of uncontrolled and unexpected ground surface movements in areas where shallow abandoned coal mines are located. The project focuses on the phenomenon of sinkholes, which is the main type of hazard affecting these regions. Seven partners, including Ineris and an associate partner, from Poland, France, Germany and Spain are participating in the SIRIMA project. In some European countries (such as France, Poland, Germany, Belgium, Spain and the United Kingdom), coal deposits are very significant and have given rise to numerous mines, some of which are still in operation. The last underground active mines are enough deep, and no sinkhole hazard should be considered. In the Upper Silesia region of Poland, the intensity of the sinkhole threat increased between 2022 and 2024, particularly above the two closed mines (Siersza and Pomorzany), which are in the final phase of their water filling process (with the flood front between 0 and 20 m). In Germany, the state of North Rhine-Westphalia is characterised by intensive mining activities that date back to Roman times and beyond. Spectacular collapses have occurred, such as the Höntrop crater in Bochum in 2000, which prompted the state to set up a risk management system for mining heritage. The mining authority is aware of around 3,700 collapses and sinkholes since the mid-1960s and estimates that around 90 incidents occur each year in the North Rhine-Westphalia region. In Spain, the situation is different. Many mines are very deep (up to 900 metres in Asturias). Coal mining has therefore followed a pattern determined by the depth of the coal seams and the economic viability of the extraction methods. Coal mines located at depths between 0 and 150/200 metres are not generally mined using underground methods, but rather by open-cast mining. As a result, sinkholes affecting former coal mines are non-existent.

As part of the project, 6 Work Packages are planned, which organize the work on subsequent aspects of the hazard of formation of the sinkholes. Work Package 2 concerns the creation of databases, including one relating to sinkholes. WP4 involves an in-depth analysis of the data collected in WP2, with a particular focus on estimating the risks associated with sinkhole formation in post-mining areas. In parallel with the work in WP4, advanced research will be conducted using machine learning (ML) and deep learning (DL) methods as part of Work Package 5.

The SIRIMA project aims to reduce the frequency and effects of sinkhole-related risks and to develop methods and tools to assess the risks associated with their occurrence. This translates into the safe use of post-mining areas by their inhabitants, who, long after the mine has closed, are unaware of the dangers that exist in these areas.

2.2. The sinkhole database (Vuidart and al, 2025)

One of the objectives of the SIRIMA project is the creation of a database of sinkholes that have occurred (Work Package 2) linked to shallow abandoned coal mines in Europe including those due to the collapse of old mining shafts. Therefore, the objectives of the database are:

- Collecting the maximum number of well-documented cases across the Partner's countries including information on the circumstances of the occurrence of sinkholes.
- Constructing Web-map for displaying of the identified cases at different scales: sub-regional, national and continental one.

The first step was to define the data that would be collected. Ineris has identified the criteria relating to the predisposition of occurrences (depth, date, nature, etc.) of mining work and the intensity (diameter, depth, etc. of disorder) of the listed sinkholes. Some data are quantitative (diameter, depths, etc.), while others are qualitative (resistance of the overburden...). For qualitative parameters, glossaries are provided in order to standardise the database and facilitate data entry. To ensure a comprehensive analysis for the other work packages, the database includes a vast array of parameters organized into five main thematic groups:

- Localization (12 data points): This group focuses on the precise identification of the event. It includes unique IDs, names, and various coordinate systems (local X/Y and WGS84). It also records the name of the mine, the country, and the specific municipality where the sinkhole occurred.
- Sinkhole Characteristics (10 data points): This section quantifies the physical disorder. Key fields include the number of sinkholes in a given area, the total impacted surface area (m²), dimensions (length, diameter, width), and the depth of the crater. It also tracks whether the data is an in-situ measurement or an estimation, the date of appearance, and the presumed origin of the collapse (e.g., failure of the roof, pillar, or shaft head).
- Characteristics of Mining Work (12 data points): This theme links surface disorders to underground activities. It records the type of mining work (shaft, cavity, or drift), the start and end dates of exploitation, the dip of the coal seam, and the depth of the workings relative to the surface. It also includes technical details like ground support types and the accessibility of the cavity for inspection.
- Overburden Characteristics (5 data points): These fields describe the geological layers between the mine and the surface. Parameters include the geology of the overburden, the fracture condition of the roof, rock strength, and water conditions (e.g., dry, seepage, or flooded).
- Surface Consequences: Finally, the database records the presence of buildings or infrastructure in the affected area and any observed damage to human property.

The database is structured using an MS Excel format, featuring several dedicated tabs: the "Sinkhole DB" for data entry, an "explanations" tab to define each field, and an "Explanatory diagrams" tab to assist partners in filling out the records accurately. The structure was finalized and validated by project partners in December 2024.

The second step was to populate the database. Ineris, acting as the lead for database creation, received national datasets from each project partner.

The German contribution, managed by DMT-THGA, focuses exclusively on the Ruhr coal mining basin. Data was primarily sourced from the "Gemeinsamkeit" project (recorded between 2015 and 2018) and the Department of Geoinformation, Surveying, and Cadastre of the city of Essen. The primary obstacle in Germany is that sinkhole data is classified as sensitive, which restricts public access. Furthermore, current regulations only allowed for the release of data from Essen for the period between 1991 and 2010. A major technical limitation is that existing databases often fail to distinguish between natural sinkholes and those caused by mining, leading to uncertainties in the final dataset. 397 cases have been entered into the database, but the associated information is very limited. In most cases, only the location of the sinkhole is available.

The Polish contribution was managed by Central Mining Institute. The Polish dataset, centered on the Upper Silesian Coal Basin (USCB), contains 906 records from three abandoned mines: Siersza, Kazimierz-Juliusz, and Jan Kanty. Information was extracted from archival mining materials, including coal seam maps and shaft profiles. Recent entries were supplemented by a 2023 inventory conducted by the Polish Geological Institute (PIG-PIB) using LIDAR technology, satellite imaging, and archival photographs. A major challenge is the loss of 19th and early 20th-century data, as surface damage was historically neglected. Systematic record-keeping only became mandatory in 1967 and was further refined in 1994, leaving vast historical gaps. Additionally, many older records lack essential technical details, such as the depth of mining operations or the direct connection between a sinkhole and specific underground voids.

Ineris recorded 512 sinkholes affecting approximately fifty mines across metropolitan France, with a high concentration in the Messeix coal basin (Centre of France). Data was pulled from the GEODERIS database (BDSTM), hazard studies, expert assessments from the last 20 years, and archives from former operators. Collecting and cross-referencing information from multiple sources was described as "tedious and time-consuming". Many sinkholes are several decades old and affect former mining works (prior to 1900), which means that technical data on overburden, mining methods, and the dimensions and depths of mining structures

are often lacking. Furthermore, most old mining works are physically inaccessible, limiting investigations to surface visits that cannot verify the state of underground cavities.

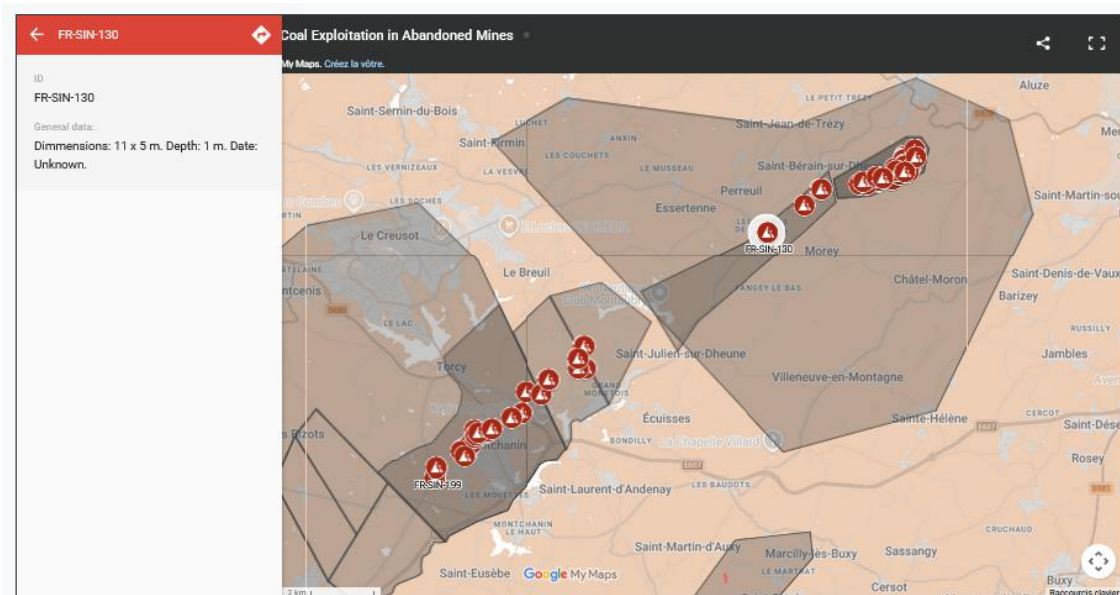
As of December 2025, the database successfully integrated 1,814 sinkholes from underground coalmines from three European countries (Figure 5). The partners continue to expand the database. The database will be analysed in work packages 4 and 5 of the project in order to highlight the main parameters that play a role in the occurrence of sinkholes in shallow European coal mines, with the aim of improving their prediction.

The third step consisted of implementing the database as a specific web map accessible to the public on the project website, accompanied by a description of how the data are used. It was initially decided to include only certain general data on sinkholes from the database into the integrated map of shallow mining operations in the partner countries: the ID of the sinkhole, its the dimensions, its depth and the date of occurrence.

The final graphical visualisation of the Sinkhole Database is publicly available as a map at the following link: <https://sirima.gig.eu/integrated-map/>.



a-



b-

Figure 5: Visualisation of the sinkhole database across partner countries (a), including supplementary data. Examples from France (b)

3. Results and Discussion

By December 2025, the database had successfully incorporated the data of 1,814 sinkholes from 3 European countries: France, Poland and Germany. One can notice that the availability and richness of information vary considerably from one European region to another.

The work carried out by the partners highlights the difficulty of obtaining complete information due to data loss over time. As a result, the sinkhole inventory is not exhaustive, as some mines are very old and information about them has not been archived. Furthermore, in Germany, not all data is public. This means that not all fields in the database could be filled in. Although the local geology is relatively well known, it is also difficult to obtain accurate information on the mechanical characteristics of the overburden, the state of fracturing and the hydrogeological situation. This information is only partially available for the French cases and is missing for the Polish and German cases.

Nevertheless, experience and the literature highlight the importance of these parameters in the occurrence of sinkholes.

It should also be noted that the German and Polish partners chose to focus solely on certain mining basins with a high density of sinkholes. In contrast, the situation in France is different. Indeed, former coal mining basins of a similar size to those in Poland or Germany generally have few sinkholes compared to their size. This can be explained in part by the structure and depth of these deposits, and the mining methods used, which left very few mine voids. By contrast, mainland France contains numerous smaller legacy mines with operations located close to the surface.

As mentioned earlier, the database provides information that will be used in work packages 4 and 5, in particular to develop prediction tools. Nevertheless, Ineris has carried out a preliminary analysis of the cases already recorded in the database. Useful observations for the next stage of the project can already be made.

It appears that the database is very heterogeneous, despite efforts to standardise the format, the terminology and the nature of the data entered. It is also noted that the number of observed sinkholes varies considerably for French sites. In particular, for sites with few recorded cases, two explanations can be put forward:

- The necessary conditions for sinkholes formation were not met.
- The information was lost or not collected.

The sites selected to populate the database were not chosen at random. For Poland and Germany, the choice fell on mining areas where sinkholes are numerous, recurrent and problematic because they are located in urbanised areas. For France, priority was given to sites for which sufficient and usable information was available. This approach, based on data availability, introduces a selection bias, as the best-documented events are likely to be overrepresented. The results of the analyses must therefore be interpreted taking this limitation into account. Furthermore, the German and Polish cases, which are concentrated in a single mining basin, may also introduce a bias in the analysis, as certain parameters are specific to these sites.

The database does not include the surface area of underground workings in the mines studied. The absence of this information also introduces a bias into the comparative analysis. Indeed, an identical number of cases in a large-scale basin or in a very small mine does not have the same statistical significance. This limitation is accentuated by the mining method used and, consequently, by the extent of underground workings and the density of residual voids.

All cases concern coal mining sites. As extraction methods are specific to each deposit and the geology is similar (most coal deposits date from the Carboniferous period and have fairly similar geology), the dataset therefore focuses on a set of very similar characteristics. This point must be taken into account in data analysis and the development of prediction tools, particularly if users plan to implement them in other types of mining works.

Finally, the database lists sinkholes affecting former underground mining works as well as mine shafts. Before processing the data, it is essential to distinguish between these two scenarios.

The next step involves analyzing the data within the SIRIMA project to develop sinkhole prediction tools. Traditional statistical methods and advanced analytical techniques such as machine learning will be implemented.

4. Conclusion

The paper recalls that main post-mining hazard is sinkhole. It can be occurred years after closing the mine. Risk assessment studies conducting for abandoned mines in France highlighted that 80% of risk areas are affected by sinkholes are reported and that around ten new cases ones appear each year.

The prediction of the sinkhole hazards is mainly based on expert judgment and historical data. For this reason, in the frame of SIRIMA European project a data base was established presenting the first European mining sinkhole database.

As in many European countries, predicting the occurrence of sinkholes is crucial to managing this issue effectively at former mining sites. One of the objectives of the European SIRIMA project is to provide prediction tools. The development of these tools is based on available information and feedback. The creation of a database is a key step in this work. France has many mining sites, with a wide range of substances being extracted, not just coal. The database contains 1,814 sinkholes from 3 European countries: France, Poland and Germany. Filling in all the information is a challenging task due to the age of the mines and the loss of information.

The work carried out as part of the SIRIMA project will contribute to the ongoing discussions on improving the assessment of sinkhole hazards.

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Health and environment approach of French post-mining management

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Abstract

Former polymetallic mining districts present health and environmental concerns due to high geochemical background and pollution associated with mining activities. In France, health and environmental studies allow to assess the compatibility of land use with environmental media to guide post-mining management. This work follows a national methodology combining land-use reconnaissance, environmental investigations, and interpretation of environmental degradation that can lead to a Quantitative Health Risk Assessment. Three case studies in southern France illustrate this framework which is based on measured concentrations and local exposure scenarios. The results show that ingestion of soil and locally produced foodstuffs generally constitutes the dominant exposure route for surrounding populations, while particle inhalation remains of secondary importance when mining residues are vegetated, without significant deposit activity. Case studies indicate that health risks are mainly associated with lead, arsenic, and cadmium. Bioaccessibility measurements help refine exposure estimates and reduce uncertainties, although recent revisions of toxicological reference values for inorganic arsenic significantly influence risk assessment outcomes. Overall, these case studies confirm the relevance of integrated health and environmental assessments as decision-support tools for defining proportionate, site-specific management measures. This article also highlights the opportunity for regular updates in light of evolving scientific knowledge and climatic conditions.

Keywords; Metals, Post-Mining, Health risk, Exposure routes, Environmental management, Bioaccessibility

1. Introduction

Old polymetallic mines are of particular concern because their mineral paragenesis results in high natural geochemical background levels (Seifert & Sandmann, 2006). Metal mobility in the mining wastes is driven by the geochemical and mineralogical characteristics of ore deposits and weather conditions. Metals and metalloids can be released and can contaminate environmental media. Metals can be transferred via aqueous pathways through leaching, infiltration, and surface runoff, thereby impacting surface waters and groundwater (Navarro et al., 2008). Fine metal particles can also be dispersed by wind (Iavazzo et al., 2012). Meanwhile, metals from soils or from contaminated irrigation water can accumulate in plants (Das & Maiti, 2007; Topal et al., 2021). Due to their toxicity, these contaminants may pose health and ecological risks (Sogos et al., 2025).

Following the European Directive 2006/21/EC on the management of waste from extractive industries (the so-called 'MWD' – Mining Waste Directive) (EU, 2006), Member States had to ensure an inventory of closed waste facilities, including abandoned waste facilities. In mainland France, 2109 polymetallic tailings were thus identified, and 233 districts within main tailings were clustered, were ranked according to their potential impact on the environment and public health (Chapon et al., 2023). To date, around forty polymetallic mining areas with the highest potential risk have undergone complete health and environmental studies. These studies are based on the French methodology for managing contaminated land (MEEM, 2017) and its approach called Assessment of the State of Media Quality (Interprétation de l'Etat des Milieux-IEM). The studies aim to evaluate, for a mining district, the compatibility between the current quality of its environmental media and its current land uses. Ultimately, the resulting general management of pollution seeks to define recommendations for mitigation measures or monitoring.

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This paper presents the general approach related to health and environmental studies and three case studies for which this kind of study has been implemented. These mining areas have been chosen among areas that have been subject to studies currently being communicated to municipalities, local authorities and population. Reports of these studies are available on GEODERIS website (GEODERIS, 2020). GEODERIS is the public interest organisation that conducts studies on behalf of the French government. It has performed closed waste facilities inventory and since 2012 implemented health and environmental studies. These studies are carried out by working groups composed of experts from GEODERIS, INERIS, and BRGM.

The overall objective of this article is to bring an overview of the application of the approach, and highlight its specific features, and its limitations, focusing on the study of human exposure and health risks for populations.

2. Materials and Methods

2.1. Methodology related to health and environmental studies

The IEM approach involves 3 main key steps: (1) land use reconnaissance, (2) field investigations, (3) interpretation of environmental degradation that can lead to a Quantitative Health Risk Assessment. These steps aim to provide decision-making support, incorporating health recommendations.

2.1.1. Land use reconnaissance

This initial phase consists in identifying current land uses to determine the populations to protect and their current and future land uses such as housing, agriculture or tourism.

Land use step consists of identifying, locating, and concretely characterizing the human activities and stakes present on the mining site and in its environment. This approach is based on field visits, generally supplemented by interviews with local stakeholders (municipalities, residents, farmers, etc.). Although it does not constitute an exhaustive inventory, it allows the land uses to be established for the study period.

This phase is illustrated by a conceptual site model to describe the relationships between the sources of pollution, the transport pathways (rainwater runoff, bioaccumulation, etc.) and exposure routes (soil ingestion, vegetable consumption, etc.) and the receptors (the types of exposed populations). Discussion of this comprehensive diagram helps to prepare next step related to site investigations by focusing on areas where exposure to possibly degraded environmental compartments is suspected.

2.1.2. Field investigations

Distinguishing the natural geochemical background from the anthropogenic geochemical background is a prerequisite to assess mining-related media degradation. So, in addition to all the available information related to the local geology and lithology, first field investigations are conducted, in parallel with land use reconnaissance, to determine the natural geochemical background as reference environment, including the range of concentrations for each substance and lithology of interest.

In the framework of health and environmental studies, the general objective of field investigations is to characterize the state of the environment and verify the transport pathways and exposure routes defined in the preliminary conceptual site model,

To achieve this, an extensive field campaign is performed to collect samples across various environmental matrices: mainly including as exposure media for populations, soils, groundwater, and locally grown plants, and for environmental impacts interpretation, mining residues, surface water and sediments. The collected samples are then sent to accredited laboratories for comprehensive physico-chemical analyses to precisely quantify the presence of targeted pollutants, primarily heavy metals and metalloids. The substances sought correspond to potentially contaminating elements carried by the mineral phases of the deposits mined in the area under study.

2.1.3. Interpretation and Quantitative Health Risk Assessment

Measured concentrations are then compared with reference environments to distinguish mining-related pollution from natural mineral anomalies, highlighting any degradation caused by former mining or associated industrial activities. In accordance with the methodology, in the absence of suitable regulatory values for soils in France, and when concentrations exceed local reference environment, a Quantitative Health Risk Assessment (QHRA) is performed. This assessment is based solely on measurements conducted in the populations' exposure media. No transfer or exposure modelling is carried out. Besides, no health risk calculations are performed for groundwater because the measured concentrations are directly compared to regulatory values for drinking water to identify any metal degradation.

Health risk assessment specifically aims to quantify chronic exposure using toxicity reference values (TRV) and exposure scenarios to calculate hazard quotients (HQ) for threshold effects and "individual excess risk" or cancer risk (CR) for non-threshold effects. Updated conceptual site models according to field investigations are used to develop site-specific exposure scenarios. Based on the identified uses, typical profiles of exposed populations are created (e.g., "child of a permanent residence", "adult gardener") considering the associated exposure routes. Exposure parameters such as exposure frequency are generally chosen according to a conservative approach.

QHRA is followed by an uncertainty analysis for putting risk assessment results into perspective, as it helps to validate the conclusions and identify the most significant uncertainties.

Ultimately, the goal is to define mitigation measures for pollution management and exposure reduction. If an incompatibility is identified, this leads to management recommendations, use restrictions, or safety measures.

2.2. Case studies

2.2.1. Preamble

To illustrate this framework, three case studies located in the South of France are presented. Aiming to examine the specific features of human health and environmental studies in a post-mining context, the analysis of the following case studies focuses on the interpretation of heavy metal concentrations contained within mineral paragenesis and associated with mining operations and in exposure environments related to humans.

It is, however, important to emphasize that the selected case studies also addressed all sources of pollution related to mining activities and their associated contaminants, such as reagents used to extract and concentrate target metals, as well as ancillary facilities such as hydrocarbon storage tanks or transformers. These case studies also considered acid mine drainage, a phenomenon commonly encountered at mining sites involving sulfide minerals. Among case studies, high concentrations in exposure environments for livestock have been identified and addressed in liaison with the French health and veterinary authorities. But these last issues are not addressed within the scope of the present article.
















2.2.2. Case study 1

The study area covers approximately 100 km² in a mountainous territory. Across the various mining concessions, extraction activities were carried out between 1848 and 1963, primarily focusing on the exploitation of zinc, lead, silver, and copper ores.

Given the extent of the studied area, the knowledge of land uses made it possible to refocus detailed investigations on 17 specific zones (representing a total of 3 km²) where potential incompatibilities between the state of the environments and land uses were anticipated. As seen in Table 1, the land uses identified are highly diversified and are divided into several categories:

- Daily life activities such as permanent or temporary (secondary) residences, vegetable gardens, public spaces accommodating children, lawns.
- Agricultural activities: including pastoralism which is the predominant activity with the summer pasturing of cattle.
- Leisure and tourism activities: hiking, camping/bivouacking, caravanning, fishing, and fruit picking.
- Water use: drinking or domestic use.

Table 1: issues identified for all investigated areas gathered in the conceptual site model (source: GEODERIS)

Pictogram	Land use	Pictogram	Land use
Daily life activities			
	Permanent or temporary residence in a hamlet		Gardening and consumption of produce for personal use
	Isolated shelter or temporary residence		Lawns where young children play outdoors
	Equipped and signposted playground		School
Agriculture activities			
	Grazing sheep, cattle or horses		
Leisure and tourism activities			
	Hiking or walking and picnicking at an unmarked rest area		Bivouacking or camping
	Caravanning		Picnicking at a marked and equipped rest area
	Picnicking at a marked and equipped rest area		Fishing
	Blueberry picking		
Water use			
	Water collection for drinking and/or domestic use		

Based on the conceptual model, the study targeted specific human exposure routes:

- Ingestion of water (groundwater or surface water) that is potentially contaminated.
- Ingestion of surface soil, which particularly concerns children under 6 years of age (due to their natural hand-to-mouth behavior), but also adults in the context of their gardening or leisure activities.
- Ingestion of potentially contaminated plants such as fruits and vegetables grown in local vegetable gardens.

Particle inhalation (outdoors or inside dwellings) has been identified as a potential exposure route, a priori only for 1 of the 74 exposure scenarios. As the study of this route requires specific sampling protocols, these were not implemented in this case study, although it cannot be ruled out that this is a significant exposure route. So, the study only focused ingestion route.

To characterize the exposure media and reference media, measurement campaigns were carried out on the following matrices:

- Soils sampled at the surface (0-3 cm) for leisure areas, and at a greater depth (0-30 cm) for vegetable gardens.
- Water including both surface water and groundwater.
- Plants including vegetable crops (fruits and vegetables intended for home consumption).

Based on the mining history, the main analyzed parameters in the matrices were the metals and metalloids linked to the mineral extraction activity: lead (Pb), zinc (Zn), antimony (Sb), silver (Ag), arsenic (As), cadmium (Cd), copper (Cu), and titanium (Ti). Metals were systematically selected for the quantitative health risk assessment (QHRA). For three quarters of scenarios involving soil and vegetable ingestion by adults gardening, risk is only associated with arsenic.

Bioaccessibility measurements were carried out on soil samples and vegetable crop samples for arsenic, lead, cadmium and antimony considering Unified Barge Method test. These analyses demonstrated that the bioaccessibility of metals and metalloids was not complete and was found to be between:

- 10% and 60% for arsenic and cadmium.
- A few percent to 20% for antimony.

- 10% and 100% for lead.

The main objective of these measurements was to refine the Quantitative Health Risk Assessment related to the soil and vegetable soil. Indeed, bioaccessibility allowed to adjust the exposure assessment. In a standard risk calculation, it can be considered by default that 100% of the ingested pollutant is assimilated by the human body. Measuring bioaccessibility makes it possible to define the exact percentage of the toxic element that will actually be "available" and absorbed by the body during digestion (Baranger et al., 2016).

Recommendations were primarily formulated for plots showing an incompatibility between land use and the media quality, while taking uncertainties into account. These may include the installation of fences to prevent access to mining deposits or remnants, or information panels indicating their presence, as well as the development of off-ground playgrounds for children. In the case of kitchen gardens, redevelopment through the addition of clean soil is proposed in order to limit exposure to pollutants originating from soils and homegrown vegetables. In some cases, it may also be recommended to prevent the remobilization of contaminated soils, in particular by maintaining vegetation cover.

2.2.3. Case study 2

The exploitation covered an area of 3700 hectares. In this mining sector, operations have mainly focused on the extraction of lead and zinc ores (often associated with silver and germanium), as well as iron pyrite.

Local populations (adult and child residents, workers, tourists) can be exposed to media through a wide variety of land uses. These uses were specifically recorded at private residences and collective spaces:

- Soil use: It includes the maintenance and use of ornamental gardens, the use of play areas for children, gardening in vegetable gardens, as well as outdoor recreational and leisure activities (hiking on trails, mountain biking).
- Water use: Surface water and groundwater are captured for domestic uses such as watering vegetable gardens and filling swimming pools (bathing).
- Food production and consumption: this includes mainly the consumption of plants grown on-site.

As particles can be re-emitted by the wind or by disruptive activities such as earthworks and mountain biking, particle inhalation has been identified as a potential exposure route in addition to soil, water and plant ingestion. So, specific measurement campaigns targeting fine particles (<10 µm) and atmospheric fallout were conducted to characterize the atmospheric fluxes of dust and assess the potential impact of nearby mining deposits on the ambient air, at around 10 different locations spread across 2 municipalities. These campaigns were deliberately scheduled during the driest and windiest periods of the year to represent the most favorable conditions for dust dispersion. However, measurements have shown that as long as the deposits retain their tree cover and are not disturbed, they do not constitute a major source of airborne contamination. Thus, after field investigations, as seen in Table 2, particle inhalation has not been taken into account in the conceptual site model for the QHRA implementation.

Table 2: conceptual site model after field investigations (source: GEODERIS)

Source	Transport pathways	Exposure route	Populations
Soil	Direct contact	Unintentional ingestion of soil	Adults and children
	Soil-vegetables transfer	Consumption of self-produced plants	Adults and children
Water	Garden Irrigation	Consumption of self-produced plants	Adults and children
		Unintentional ingestion of water	Adults and children
	Swimming	Unintentional ingestion of water	Adults and children

Based on the knowledge about minerals and first metal characterization already done on different media, the analyzed parameters were: aluminum (Al), lead (Pb), zinc (Zn), antimony (Sb), silver (Ag), arsenic (As), cadmium (Cd), chrome (Cr), cobalt (Co), copper (Cu), barium (Ba), iron (Fe), manganese (Mn), mercury (Hg), nickel (Ni) and thallium (Th). The quantitative health risk assessment (QHRA) conducted for soil ingestion and home-grown consumption showed situations for which land uses were not compatible with the quality of soils and vegetables. The risk was mainly associated with lead, arsenic and cadmium and, to a lesser extent, antimony.

In addition to specific recommendations provided for certain plots where an incompatibility between land uses and environmental quality has been identified, general recommendations for the use of private spaces are

also issued. These aim to limit users' exposure to contaminants present in soil particles. The study recommends wet cleaning of indoor floors and covering bare soils with paving or vegetation in particular, which represent good practices already provided by local health authorities for people living on or near soils with high concentrations of metals and metalloids.

2.2.4. Case study 3

The study area encompasses the entire watershed of a river, which covers a total surface area of approximately 125 km². The main substances mined in this sector were iron, pyrite and lead, with mining activity mainly taking place from the mid-19th century to the early 20th century.

This case study was chosen for this article due to the presence of protected species, to emphasize the terms of study. Consequently, aspects related to human exposure are not detailed.

The study of protected plant and animal species was primarily conducted through a documentary vulnerability assessment. Researchers used databases such as CARMEN and Infoterre (BRGM, 2024) to identify protected environmental areas within the watershed. These included Natura 2000 sites, ZNIEFFs (Natural Zones of Ecological, Faunistic and Floristic Interest), a ZICO (Important Bird Conservation Area), and a Regional Nature Park.

The vulnerability of the protected species was evaluated based on the geographical position of their designated environmental zones relative to the old mining sites, prevailing winds, and potentially contaminated watercourses. The study operated under the assumption that these environmental zones effectively delimited the living perimeters of the species.

To definitively conclude on the real impact of the past mining activities on these protected species, the report recommends conducting a specific study on local biodiversity and species distribution.

As seen in Figure 1, a conceptual site model was developed, illustrating transport pathways such as particle re-suspension and accompanied by a table taking into account environmental and health issues and associated exposure routes and receptors. The report provided recommendations in terms of restrictions on the use of surface water for irrigating metal-sensitive plants on acidic soil.

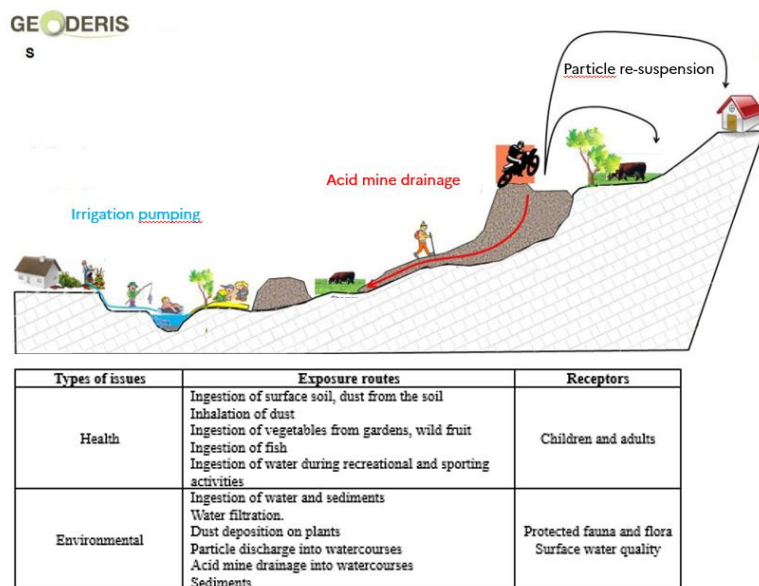


Figure 1: conceptual site model (source: GEODERIS)

3. Results and Discussion

3.1. Main exposure routes

Based on cases studies, populations near deposits are mainly exposed to metals through soil and plant ingestion and to a lesser extent to particle (or "dust") inhalation. The dispersion and deposition of particles

loaded with metallic and metalloid elements from deposits can be identified as potential transport pathways, leading to potential exposure routes via particle inhalation and ingestion. The only measurement campaigns targeting fine particles and atmospheric fallout concerned case study 2. This is certainly due to the extension of the area concerned (10 measurement locations and 2 municipalities). This could have justified the deployment of specific protocols that are therefore cumbersome to implement, in particular to ensure spatial and temporal representativeness. In any case, the interpretation of results showed that, in the absence of significant activity and with forest cover maintained, deposits are not considered as significant sources of metallic particle emissions.

Regardless of the implementation of health and environmental studies and at the request of the health authorities, a QHRA was carried out twice to assess risks related to the inhalation of soil-derived particles by populations living near a former mining district located in Orbiel Valley in South of France (Les services de l'État dans l'Aude, 2025). These studies, based on sampling campaigns and analyses of airborne metallic particles in ambient outdoor air, showed that the risks are considered not of concern for both children and adults. In 2021, in order to take into account the tools and methods currently in force at the national level, the IEM approach was also implemented, making it possible to confirm that air quality in the valley complies with regulatory requirements for residents and is compatible with residential land uses.

In the context of climate change, increases in temperature and heavy rainfall, combined with a reduction in vegetation cover, could however further promote the re-suspension of particles (Aryal & Evans, 2023; Munson et al., 2011).

3.2. Bioaccessibility

Taking bioaccessible fractions into account allowed for a downward adjustment of exposures. This was particularly decisive in significantly reducing the health risk levels associated with arsenic or cadmium, thus avoiding the issuance of overly burdensome recommendations based on overestimated risks (particularly in vegetable garden scenarios where arsenic often generated incompatibilities).

3.3. Risks and substance toxicity

Based on the two first case studies, QHRA showed that risk is mainly associated with lead, arsenic and cadmium. The IARC has classified cadmium and inorganic arsenic as “carcinogenic to humans” (Group 1) and inorganic lead as “probably carcinogenic to humans” (Group 2A) (PRC, 2021). The health effects of these substances are well documented (INERIS, 2026).

The results of the risk calculations strongly depend on the choice of toxicological reference values (TRVs) based on current scientific knowledge. Beyond the choice of toxicological value for risk assessment, there are many sources of uncertainty associated with determining these values. Given the exposure durations considered, the TRVs chosen for the risk assessment correspond to chronic TRVs. For arsenic, chronic TRVs are established for inorganic arsenic, although total arsenic concentrations are used for risk assessment, which is a conservative choice. The U.S. EPA has recently revised the non-threshold TRV for inorganic arsenic (U.S. EPA, 2025). The value has thus changed from $1,5 \text{ (mg/kg/j)}^{-1}$ to $31,7 \text{ (mg/kg/j)}^{-1}$, corresponding to a twenty-fold increase. This results in a significant impact on risk indicator values and on the conclusions of recent studies taking into account this new TRV. In addition, this recent toxicological review may challenge the relevance of bioaccessibility measurement for this metalloid; the conclusions on risks becoming similar in most cases, regardless of whether bioaccessibility is measured or not.

3.4. Management measures

Case studies provide examples of recommendations that are provided to reduce or “cut” people exposure to contaminated sources or to the impacted environments with which populations may come into contact. This translates concretely into the implementation of specific site management plans and measures (Chapon et al., 2023).

Management plans are proposed to restore compatibility between observed land uses and the actual state of the environmental media. Control of pollution sources and transport pathways represents a key element. Measures can be recommended to limit erosion and the dispersal of mining residues, notably through the implementation of covers or stabilization structures. Control of water flows (surface runoff, infiltration) can

be also recommended to restrict the transfer of metals and metalloids toward surface water and groundwater. Regular monitoring of groundwater is necessary to verify the effectiveness of these measures. Simple management measures can be proposed by limiting transport pathways when adverse effects are likely to occur, and by disseminating hygiene advice to limit the population exposure to dust or contaminated soil, especially for sensitive populations. In addition, the memory of sources and contaminated zones is maintained by informing future developers and residents, in case of change of use in particular. Finally, in terms of administrative and regulatory management, land-use restrictions may be recommended and implemented to lock in uses compatible with the state of the environment, in particular while waiting a management plan.

3.5. Ecosystem assessment

Regarding the third case study, environmental assessments of ecosystems have primarily considered ecologically significant areas based on the presence of protected species through a documentary vulnerability assessment. As mentioned in the report related to this case study, a specific study on local biodiversity and species distribution would complement this assessment.

Furthermore, ecological approach could be combined to chemical and ecotoxicological approaches to assess ecosystems risks. The standardized method for soil quality assessment (ISO 19204:2017) describes the procedures for implementing various tools derived from these three distinct approaches and thus characterizing risks for living organisms. On top of that, ecosystem assessment has become fundamental within the framework of the European Soil Monitoring Law, as it makes it possible to quantify soil health through their biological functions and their capacity to provide essential ecosystem services, such as carbon sequestration and water cycle regulation (EU, 2025). As with human health risk assessment, ecosystem risk assessment could serve as a decision-support tool for managers and thus contribute to assessing the environmental impacts of former mining sites.

4. Conclusion

Analysis of three case studies confirmed the relevance of health and environmental assessments as decision-making tools, supporting recommendations such as site-specific management plans and measures to reduce exposure.

These studies are based on current knowledge, and the results of these studies are associated with uncertainties, mainly related to the predictive estimation of population exposures. The measured concentrations in exposure media, as well as the toxicity of the pollutants to which populations are exposed, constitute key parameters. Bioaccessibility can reduce uncertainties in decision-making, by providing more realistic estimates of exposure and risk levels. However, the recent evolution in the assessment of inorganic arsenic toxicity may challenge the relevance of bioaccessibility measurements for this metalloid.

Additionally, with regard to the ecosystem assessment, future approaches could evolve toward integrated methodology combining chemical substance analysis, ecotoxicity of environmental matrices, and ecological evaluation.

More generally, the evolution of scientific knowledge and of the climatic context could ultimately lead to the updating or supplementation of these studies, in order to ensure the robustness and sustainability of their conclusions and thereby confirm the relevance of the management measures.

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Monitoring of Sinkhole Hazard as a Tool for Risk Management on Post Mining Lands

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Abstract

Shallow underground mining in Europe have left significant voids in the rock mass. These voids pose a risk of sinkholes in abandoned mine areas. They also pose a common hazard to buildings, road and rail structures. Methods for monitoring the stability of voids are severely limited due to the lack of direct access to abandoned mine workings. Therefore, the only rational way to control the behavior of underground voids is to document and monitor the phenomena and processes occurring in the rock mass within areas of shallow mining. Phenomena that require documentation include sinkhole occurrences, spatial characteristics, processes occurring in the rock mass surrounding the voids under the influence of water content and the impact of dynamic loads such as groundwater flows and vibrations generated by seismic waves. The research project "Sinkhole hazard and risk management in post-mining areas" (SIRIMA) is dedicated to standardizing research, monitoring, and sinkhole risk management methods in abandoned, underground mines. The project is partly funded by the European Union under the Coal and Steel Research Fund (RFCS) and covers post-mining regions in France, Spain, Germany, and Poland. This paper presents methodology and the first results obtained in project.

Keywords: Environment, Post-Mining, Sinkholes, Hazard, Monitoring

1. Introduction

As a result of underground mining, various types of surface deformations are observed. They are divided into continuous and discontinuous. Continuous deformations may take the form of subsidence and uplift and cover large areas of land. Subsidence usually occurs during mineral extraction and lasts for a certain period of time after its completion (usually up to 5 years) (Dudek et al., 2022; Tajduś et al., 2021; Kwiatek 1998). In a longer period of time, and also when the drainage of the rock mass ceases (after mine closure), a partially reverse process may occur, i.e. land uplifting (Tajduś et al., 2023; Kotyrba et al., 2024). The flooding of shallow mines creates the highest risk of sinkhole occurrences. The water saturation changes the physico-mechanical properties of rocks and initiate secondary collapses of voids in the rock mass can which travel to ground surface. This, opens up the possibility of sudden ingress of water from surface floods into underground voids.

In areas where mining origin subsidence has previously occurred, the reverse process such as uplift, should not affect the development of the area due to its small rate. The situation can be different in areas of former, shallow mining. In these areas there are large amounts of empty cavities left in the ground, filled with gas (air) or water. The voids left may have various spatial shapes, from simple to very complex ones. The risk of sinkholes is particularly high when the water flooding the mine approaches the rock mass top. This phenomena is observed in many post-mining regions. It should be mentioned here that the sinkholes may appear in areas where no mining operations were carried out. The origin of such events lies in the wash-out of near surface material by natural or anthropogenic waters infiltrating the soil. Such processes create voids in sub-soils which can cave in and appear as the sinkholes at the surface.

Sinkhole can be hazardous to human life and property due to its tendency to occur without warning. (Singh et al., 1997; Papadopoulou-Vrynioti et al., 2013). The risk depends on various factors. The main ones are: the methods of mining, the dimension of voids created, the depth of exploitation, the thickness of strata in overburden, the presence of geological disturbances, in situ stresses, surface topography, the nature of the overburden, and the solubility of rocks. Changes in groundwater levels, precipitation (climate change with extreme events) and earthquakes favour their occurrence. In Poland there is no clear definition or limit determining from what depth the void can migrate to the surface. However, most sinkholes occurred in places where the mining works were carried out to a depth of 100 m (Kotyrbka 2005). It is observed that they are especially numerous in regions where mining works were carried out shallower than 50 m below the ground surface.

The SIRIMA project focuses on increasing knowledge and experience related to the surface stability on post-mining areas in EU Member States. The main objective of the project is to reduce the occurrence of uncontrolled and unexpected movements of the Earth's surface in the areas of abandoned, shallow coal mines during their flooding. To achieve this, SIRIMA encompasses six Work Packages (WP1–WP6), covering project management, database development, analysis of mine flooding impacts, sinkhole hazard modelling, machine-learning-based predictive tools, as well as dissemination and exploitation activities (fig. 1). It is assumed that cooperation between partners from France, Germany, Spain, and Poland will significantly expand knowledge on the mechanisms responsible for sinkhole formation and their consequences, while also contributing to improved hazard and risk assessment methodologies.

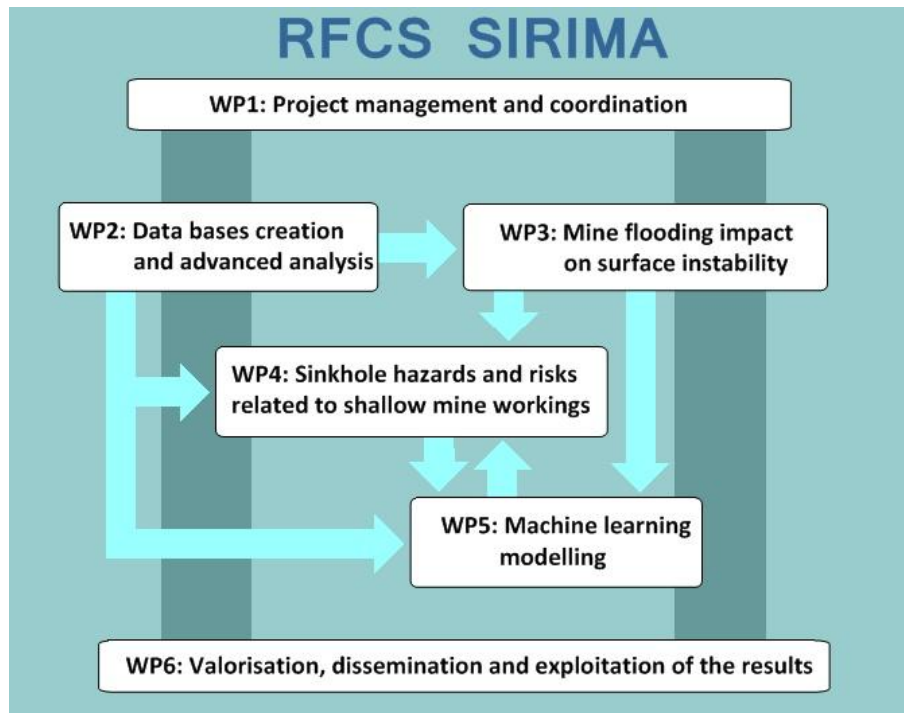


Figure 1: Graphical presentation of the SIRIMA project workflow

As part of the RFCS SIRIMA project, research and environmental monitoring are being carried out in three post mining regions. Two of them are located in areas of abandoned hard coal mines in Poland, while the third site is situated within the area of an abandoned ore mine in Thil (Lorraine, France). Both areas located in Poland lie within the Upper Silesian Coal Basin (USCB), where hard coal mining is still ongoing. Current mining operations are concentrated in the central and south eastern parts of the region. The northern and eastern parts have already been decommissioned (fig. 2). For this reason, dewatering of the rock mass has been discontinued in these zones. The rising groundwater level, combined with previous mining activities, poses a threat to the safe use of the land surface by local residents. Within the SIRIMA project, analyses of data obtained from these locations are being carried out to develop an optimal monitoring system for regions exposed to sinkhole hazards.

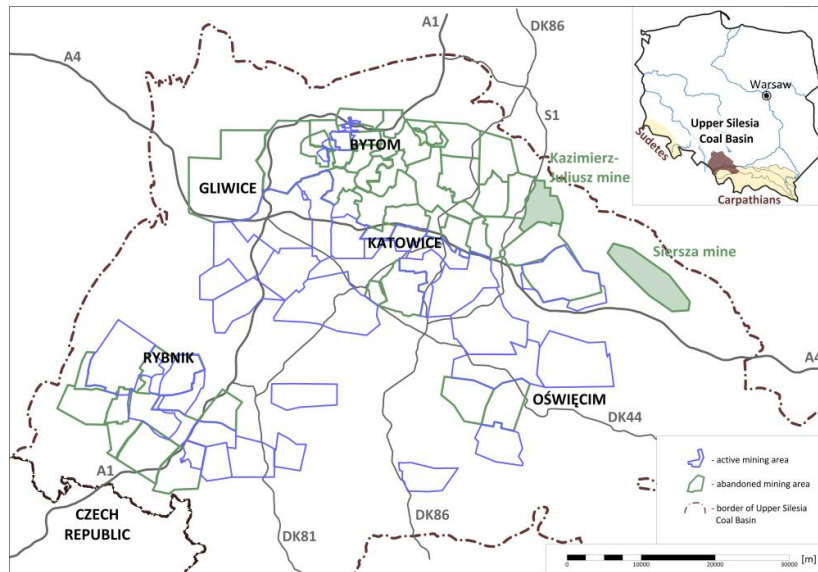


Figure 2: SIRIMA Test Sites: Siersza and Kazimierz-Juliusz on the background of active and abandoned mines in the Upper Silesia Coal Basin, Poland.

The work carried out in these research areas is complex. It also includes the development of 2D/3D numerical models using various software tools (FLAC3D, RS2, 3DEC, Abaqus). As these activities progress, models and analyses are expected to be created that will enable the assessment of conditions leading to sinkhole formation in post-mining areas. At the same time, machine learning (ML) and deep learning (DL) algorithms are being applied in the study. The analysis is based on provided archival data as well as data collected from already operating research infrastructure (Kazimierz-Juliusz) and newly established infrastructure (Siersza). The use of machine learning methods supports the forecasting of sinkhole hazards in post-mining regions. Within the project, a database of sinkholes from Poland, France and Germany (1,814 cases) is being integrated, containing geological information, mining data and geometric parameters of sinkholes. The data have undergone standardization, cleaning and gap-filling using methods such as K-Nearest Neighbors Imputer (KNN) and Iterative Imputer (IT), ensuring consistency and high analytical quality. The results of the ML/DL models will form the basis for work on hazard mapping, vulnerability assessment and the development of decision-support tools.

2. Objectives and methods

The main goal of the SIRIMA project is to enhance the risk management on areas of abandoned deep mines using new observation systems and data analysis tools. The main objectives specified in project are:

- The creation of an European database of sinkhole and the analysis of the conditions of the occurrence of the sinkhole to better manage the hazard in the future by the coal region in transition.
- Study the impact of mine flooding on surface instability.
- Identification of sinkhole hazards and risks related to shallow coal mine works.
- Developing a machine learning model to help the different post-mining actors to better predict the sinkhole hazard, this new tool is very useful for the hazard with limited data and information.
- Proposing an operation monitoring tool, integrating the communication of the hazard to public and decision makers.
- Developing an operational guideline for the mining authorities, stakeholders, etc.

The objective of the guidelines being prepared at the end of the project (item 6) is to incorporate sinkhole hazards into the risk-management system and the sustainable development of coal regions undergoing transition and intended for post-mining land use. To protect the surface of post-mining areas and to correctly assess changes occurring in the subsoil of regions where groundwater level is being restored, continuous monitoring is essential. The implementation of the European RFCS SIRIMA project addresses this challenge by combining harmonized spatial data on mining and sinkhole locations with multi-sensor monitoring data from areas threatened by discontinuous deformations (sinkholes). The integrated databases have enabled the development of a publicly accessible web service presenting post-mining regions in EU where coal extraction was carried out at shallow depths and where sinkholes may pose a significant hazard to the safe use of the land surface (fig. 3).



Figure 3: Map of abandoned coal mines with A: shallow mining areas in area of Lyon and B: sinkholes recorded in selected area of the Upper Silesian Coal Basin (USCB).
Data available at <https://sirima.gig.eu/integrated-map/>.

The monitoring system for post-mining areas developed within the project, integrating four complementary methods — seismological, hydrogeological, gravity, and geodetic observations (including satellite-based techniques) — makes it possible to track changes occurring in the rock mass during the restoration of the groundwater level.

On both test sites in Poland the monitoring system was deployed. It consists of: piezometers, seismometers and ground monitoring points (geodetic benchmarks) for annual GNSS and gravimetric campaigns. For both research sites, detailed analyses of surface deformation are being carried out using satellite radar interferometry (InSAR) techniques. Below we present the monitoring system components that were installed at the Siersza Test Site for the SIRIMA project. This area was selected due to the numerous (85) sinkhole processes observed between January 2019 and the end of 2025 in this area (fig. 4).

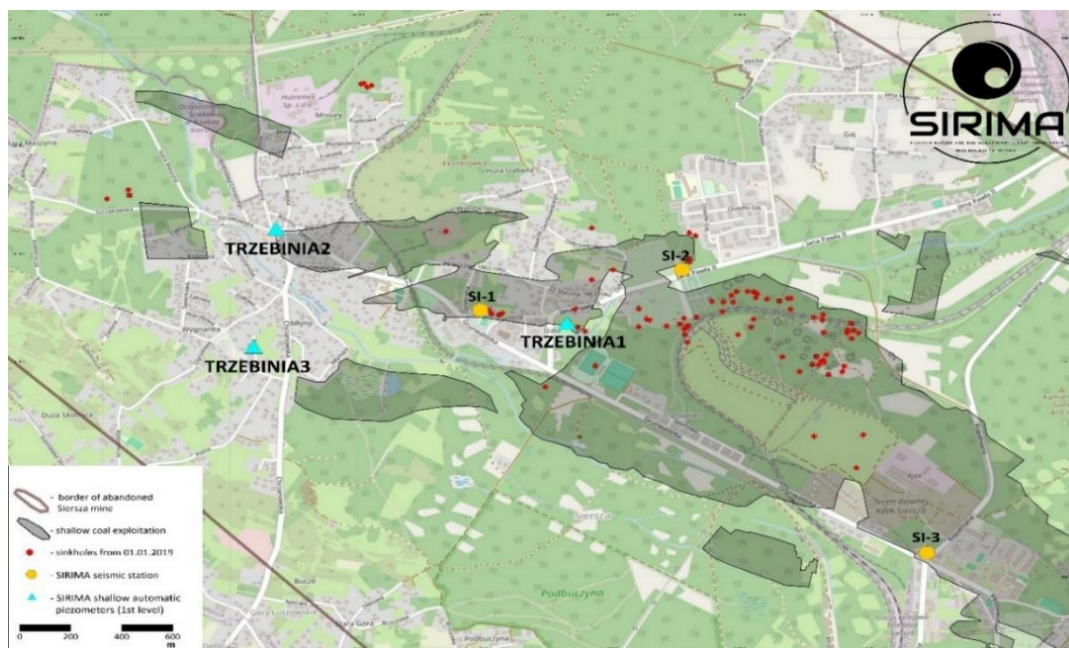


Figure 4. Location of 85 sinkholes and monitoring system components in the area of the abandoned Siersza Coal Mine.

Hydrogeological monitoring is carried out using three automated piezometers designated as Trzebinia1, Trzebinia2, and Trzebinia3 (blue triangles in fig. 4). As part of the SIRIMA project, the entire process of developing and installing this measurement equipment was completed. The purpose of the research is to observe changes in groundwater table levels within the area affected by emergency dewatering operations conducted by SRK S.A., implemented due to the sinkhole hazard associated with shallow historical coal mining in the abandoned Siersza mining area in Trzebinia. Through continuous observations of groundwater level fluctuations, the aim is to identify a direct relationship between these changes and the timing of sinkhole occurrences at the surface, where shallow coal mining took place in the past. The monitoring stations were located in such a way that, in addition to providing scientific data for the project, they also contribute to improving land-use safety for local residents.

The installation of this system at the three sites included geological works—drilling piezometer boreholes designated P1, P2, and P3—and the provision of automatic measurement stations, which were subsequently labeled TRZEBINIA1, TRZEBINIA2, and TRZEBINIA3 (fig. 5).



Figure 5. Photos documenting the installation of the TRZEBINIA2 automatic hydrogeological station at the Siersza test site of the SIRIMA project.

The installed measurement systems enable the collection of groundwater table data at a defined sampling rate (from 1 second to 24 hours) and the remote transmission of data to a server, where they are stored. Each set includes an integrated sensor for water level, temperature, and conductivity, as well as a data logger with a built-in power supply and a charging system powered by photovoltaic panels, all placed in a sealed and tamper-proof housing. The recording unit is powered by a solar panel, and in the event of a failure or insufficient sunlight, it is supported by a battery that ensures the device can operate for up to 7 days. Current parameters from the piezometric stations are available through a dedicated web application.

The seismological monitoring system installed at the Siersza test site complements the Upper Silesian Regional Seismological Network of GIG-PIB (GRSS GIG-PIB). This network consists of 39 measurement stations distributed across the Polish part of the USCB in areas of seismicity induced by mining (Dubiński et al., 2020). It enables the recording and cataloguing of seismic events with a local magnitude greater than $M = 1.5$. The accuracy of epicentre location is estimated at 1 km.

The installation of three seismological stations at short mutual distances (approximately 1 km) and of high sensitivity enhances the monitoring capabilities. The purpose of their installation is to record very weak seismic events and to correlate ground vibrations originating from induced seismicity caused by mining operations in coal mines located approximately 7–12 km to the west (Sobieski Mine) and southwest (Janina Mine) with the timing of sinkhole occurrences at the Siersza test site. Therefore, GeoSIG VE 53 triaxial seismometers with the following specifications were installed:

- sensitivity: 1000 V/m/s;
- frequency range: 0.9 Hz to 89 Hz
- dynamic range: > 125 dB (0.9–15 Hz) and > 120 dB (0.9–30 Hz)

These two systems (hydrogeological and seismological) make it possible to observe the dynamic changes occurring in the geological medium as natural groundwater levels are restored and as short term ground vibrations take place, and they operate continuously.

Changes occurring over longer time periods are monitored through periodic gravimetric surveys, supplemented by ground based GNSS geodetic measurements and analysis of archival and current satellite images (InSAR). The purpose of these measurements is to observe temporal changes in the distribution of mass within the rock mass. The rising groundwater table and the filling of post mining voids lead to an increase in the mass of the rock mass, which affects the local gravity field. Observations to date at the Kazimierz Juliusz test site (Kotyrbka et al., 2024) indicate that gravimetric monitoring is a very effective tool for identifying areas where mass changes result in the accumulation of stresses. Such areas may become zones where surface deformation phenomena (e.g. sinkholes) concentrate, posing a threat to land users.

Figure 6 shows a network of 54 measurement points established for the implementation of this task. The distribution of the points covers the entire area affected by the conducted mining operations, including the town of Trzebinia and the surrounding localities. The points, in the form of stabilized geodetic benchmarks, are arranged in a grid with a spacing of approximately 1 km.

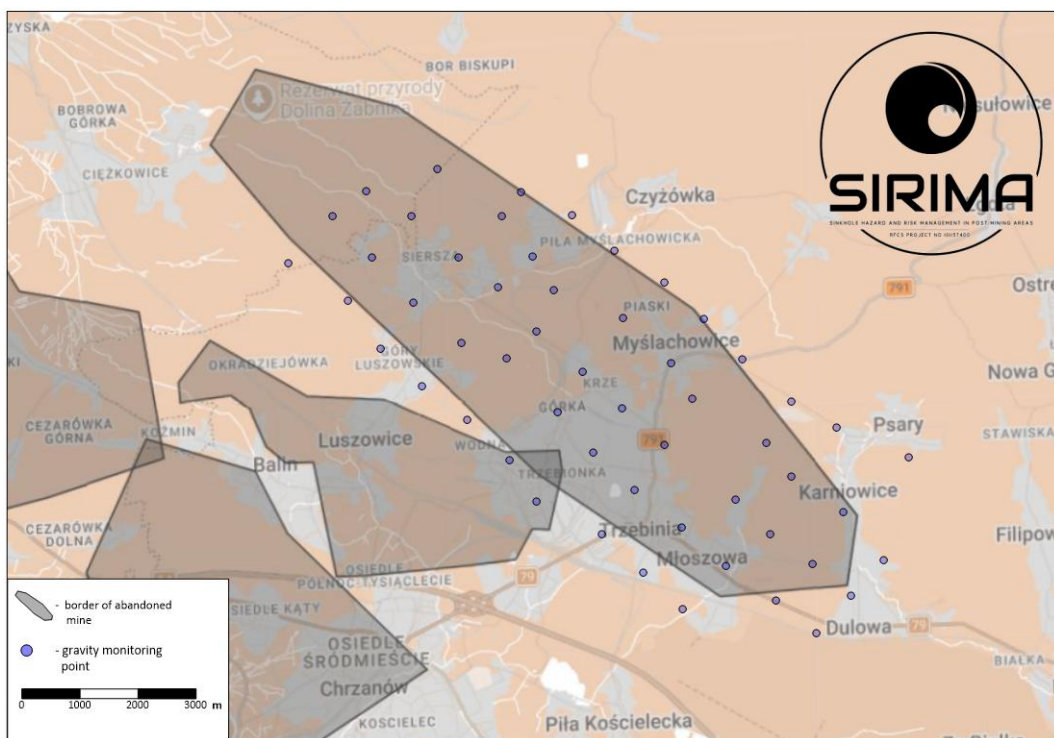


Figure 6: Gravimetric measurement grid on the selected Test Site in Poland. The grid mesh is ~1000 m.

3. Results and Discussion

During the first 18 months of the SIRIMA project implementation, work was carried out related to the construction and installation of automated measurement equipment for recording groundwater table fluctuations within the Siersza test site. The project is currently in the data collection phase. From the moment the systems were launched and continuous monitoring began, no new sinkholes occurred within the area of shallow coal mining until the end of 2025.

During this period, the observed changes in the groundwater table are relatively small, but differences between individual piezometric stations are noticeable. In the Trzebinia1 and Trzebinia2 piezometers, changes reflect the combined behaviour of Carboniferous waters (from the Carboniferous formations where hard coal mining was conducted) and Quaternary waters. It should be noted that after the series of sinkholes that occurred at the end of 2022 and in the first quarter of 2023 (37 sinkholes in 7 months), emergency pumping of water from the mine workings was initiated in order to slow down or stabilise the rate of groundwater rise. Pumping began at the end of May 2023. From that moment until the end of 2025 (32

months), approximately 50 additional sinkholes occurred. In the Trzebinia1 piezometer, the influence of this drainage activity is clearly visible, and the groundwater level fluctuates periodically within a range of ± 0.15 m (Fig. 7).

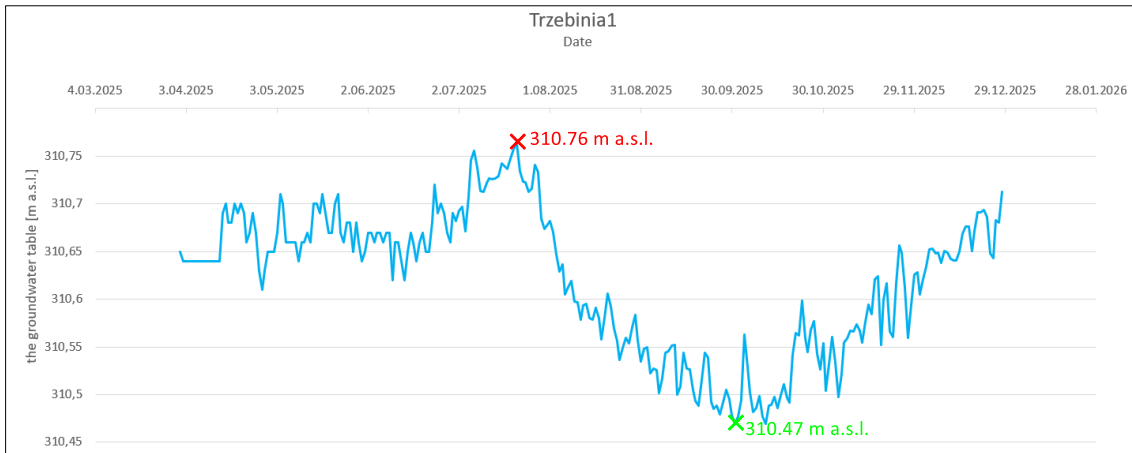


Figure 7: Groundwater table fluctuations in 2025 at monitoring point Trzebinia1.

The situation is different in the Trzebinia 2 piezometer, located farther to the west. Since the moment it was put into operation, a continuous and gradual rise in the groundwater table has been observed there (Fig.8). Over a period of nine months, this increase amounted to 0.56 m. This clearly indicates that at this point the influence of drainage activities is limited and most likely only slows down, rather than stops, the upward movement of the groundwater level. Due to the short duration of the measurements, the presented hypothesis requires confirmation.

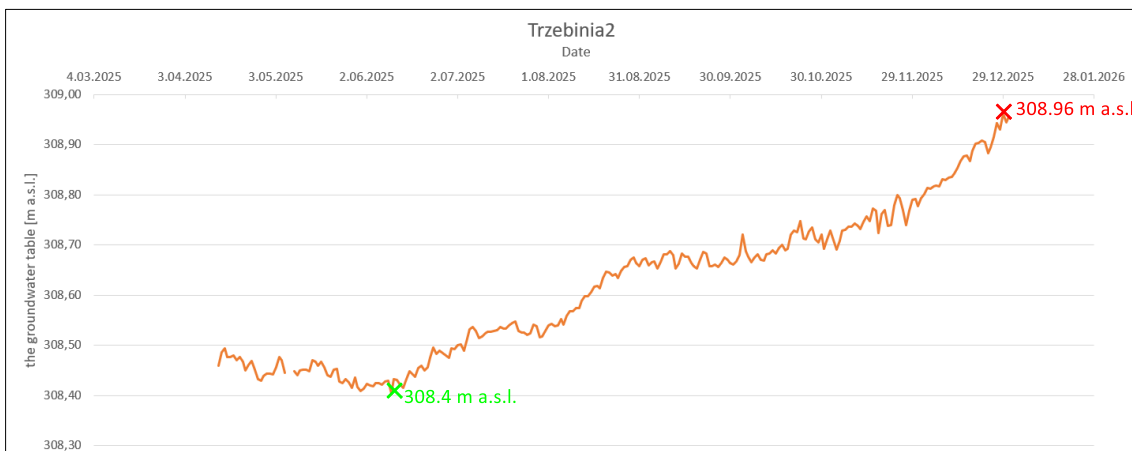


Figure 8: Groundwater table fluctuations in 2025 at monitoring point Trzebinia2.

As part of the gravity and geodetic survey campaign, the first measurement series was carried out in 2025. The gravimetric survey was conducted in August and September 2025. Having the point's heights from geodetic survey, we were able to construct Bouguer anomaly distribution map (epoch 2025.718) depicted in Fig. 9. The field gravimetric measurements are conducted by ranging, where the daily measuring cycles were referenced to a local base point. The value of the gravity force g in base point was assumed as constant and linked to earlier gravimetric studies in this area.

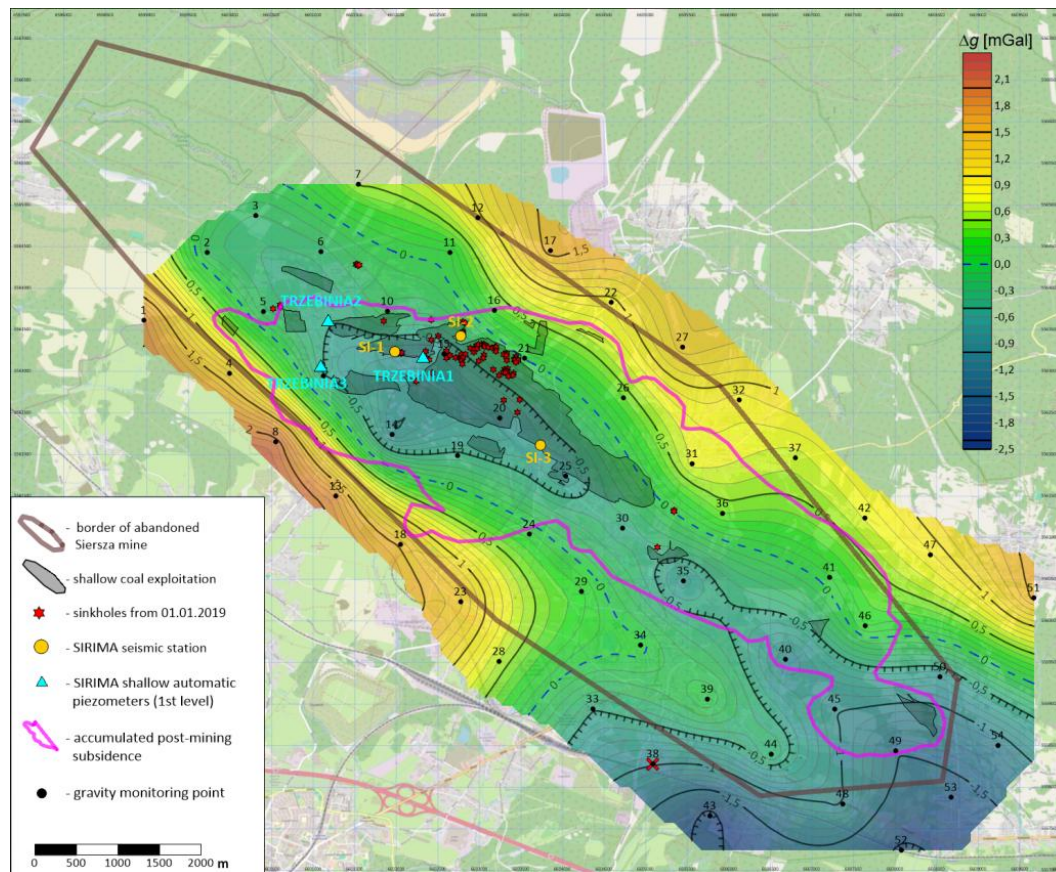


Fig. 9: Gravity, Bouguer anomaly distribution in Siersza Test Site for epoch 2025.718.

The image of the distribution of the Δg values is dominated by the negative anomaly in the centre of the site. It correlates with the shallow coal extraction zone and the sinkhole occurrence. The anomaly in the south-eastern corner is probably partially connected shallow exploitation (within magenta polygon) and partially with the presence of a local river valley here and hence less dense material in the layers closer to the surface. This fact will become less significant since switching to differential maps after the 2026 measurement campaign.

4. Conclusion

The SIRIMA project demonstrates the effectiveness of integrated monitoring systems in understanding sinkhole mechanisms in post-mining regions. Early results confirm strong relationships between hydrogeological changes, seismicity, and deformation processes. Further development of predictive tools and continuous data integration will significantly enhance safety and land-use planning in European post-mining areas.

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Geotechnical Aspects of Mining and Postmining

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Abstract

End of 2018 Germany stopped hard coal mining. This means not the end of efforts to repair the geotechnical damages caused by more than two centuries of mining. One aspect was the firefighting on waste dumps from coal mining and coal processing. Actual in Germany some dumps are only still warm. The firefighting with suspensions and covering with soil were successful. One critical aspect, there are some ten thousand openings to day ground from mining only in North Rhine-Westphalia. Many of them are in unknown condition and probably dangerous. Another aspect is the water inside the abandoned mines. The German solution for water coming from coalmines is expansive but it is under control. The same experience we have with the next aspect, the water management in subsided areas. In some other countries, we are or were involved in solving the problems with burning dumps and coal seams from lignite mining (Turkey) and with AMD (Acid Mine Drainage) in South Africa. There in South Africa is another aspect in the instability of pillars and roof because of room-and-pillar-mining near to surface. Together with the Geological Survey of South Africa, we found a solution to stabilize the pillars and to avoid AMD.

Keywords: Environment, Mining, Post-Mining, Rehabilitation

1. Introduction

Mining, especially hard coal and lignite mining, causes a lot of geotechnical damages. In Germany and some other countries these damages need to be repaired while mining is still going on and when mining has stopped. We were and partly are involved in finding solutions for the following aspects:

- Waste dumps from coal mining and processing burned in Germany (Fig. 1, 2 and 3) and China and are still burning in Poland and Turkey. In China the waste dumps from hard coal mining are not burning anymore (vocal information by CCTEG Germany). In Germany we found different solutions for the firefighting in Ruhr Area.
In Silesia, Poland, some waste dumps from hard coal mining and processing are still burning. Firefighting is not finished in the moment (vocal information by KOMAG, December 2025).
Next to Soma in Turkey dumps from lignite (brown coal) mining and processing are still burning (Fig. 4 and 5) (own pictures from 2016).
- The burning of coal seams is still a serious problem in the northwest area of China but also in the area around Soma in Turkey (Fig. 6, 7 and 8).
- In the past the openings to the surface of underground mining operations were filled with soil from the surrounding area when the shafts were abandoned. Only in Ruhr Area are more than 20,000 former shafts, more than 60,000 in North Rhine-Westphalia. Often the stability of the filling is unknown or critical (Fig. 24 and 25).
- The level of the surface of subsided areas often is below the natural level of ground water table. In this case there are three opportunities:
 - o filling up this area to get a surface above ground water table (partly in China, in Kazakhstan, partly in Germany)
 - o do nothing and there is a lake (partly in China with lakes up to 100 km²)
 - o groundwater management with pumping (German solution)

- Mine water normally is mineralized. In Germany in the area of Dortmund upcoming mine water has a very high content of Iron 2^+ and flew into the next small river called Kirchhörder Bach. In contact with Oxygen, it became Iron 3^+ and contaminated this small river. Here we had to find a solution to reduce the content of Iron (Fig. 9 and 10).
- In South Africa, province Mpumalanga, AMD (Acid Mine Drainage) is a serious problem for farmers and the municipality (Fig. 11 and 12). Due to fresh surfaces caused by mining activities the Pyrite inside the sandstone oxides and combined with rain water Sulphur acid washes out. Additional this Sulphur acid solutes heavy metals like Mangan, Chrome and Iron. In rain season this water colors the next river brown. In dry season the banks of the river became white because of the metal salts.
- Another very serious problem caused by coal mining in the system room-and-pillar is the instability of the pillars and the roofs (Fig. 11, 13 and 14). This causes subsidence at the surface, sometimes even in cities.

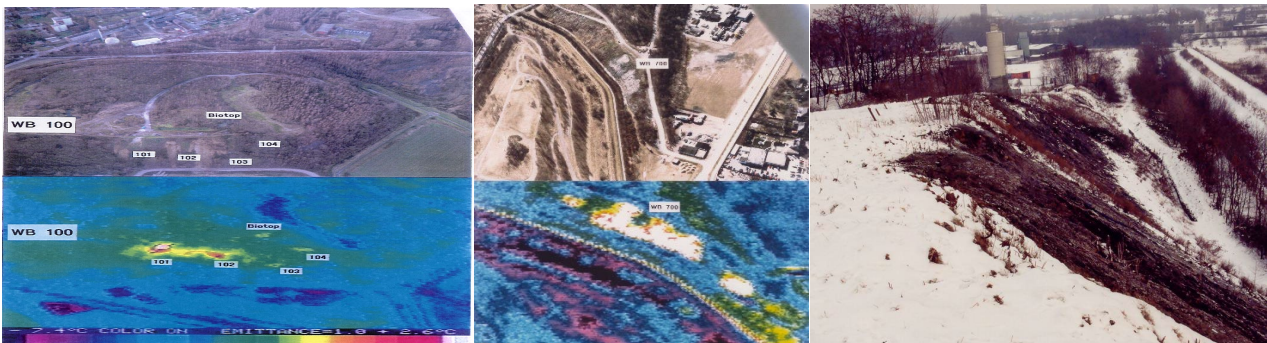


Fig. 1: Air photo and infrared photo from burning dump Rheinelbe (DMT GmbH)
 Fig. 2: Air photo and infrared photo from burning dump Graf Moltke (DMT GmbH)
 Fig. 3: Photo with snow on burning dump Graf Moltke (own picture)



Fig. 4 and 5: Steam in a crack of a burning dump near Soma, Turkey (own pictures)



Fig. 6, 7 and 8: Steam coming from cracks in the landscape above an abandoned lignite mine near Soma, Tukey (own pictures)



Fig. 9: Mine water with high content of Iron 2+ coming to the surface (own picture)

Fig. 10: Mine water entering Kirchhörder Bach near Dortmund, Germany (own picture)



Fig. 11: Acid mine water above a collapsed room-and-pillar coal mine, province Mpumalanga, South Africa (Henk Coetzee, Geological Survey of South Africa)

Fig. 12: Acid mine water with a temperature of 38° C coming to surface, province Mpumalanga, South Africa (own picture)

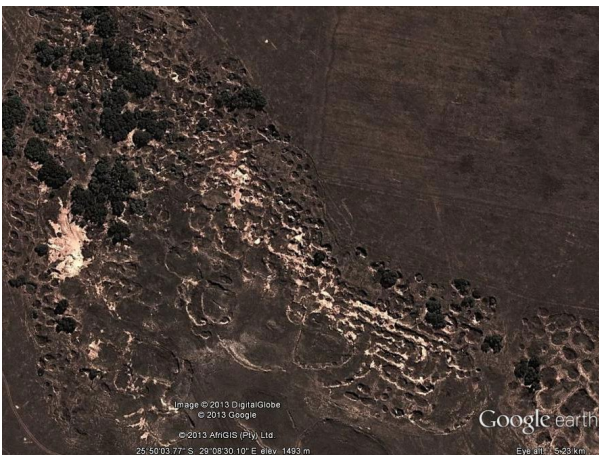


Fig. 13: Subsided Areas in Mpumalanga, South Africa (Henk Coetzee, Geological Survey of South Africa)

Fig. 14: Subsided Areas in Mpumalanga, South Africa (Henk Coetzee, Geological Survey of South Africa)

2. Materials and Methods

Each of the above introduced aspects and problems needs a special solution individual for each area. A very important factor are the costs of reparation damages. Normally reparation starts when mining has finished. The former owners of a gallery often are not available and no institution is responsible for paying. In such cases often the government has to pay.

2.1. Firefighting on burning Dumps from Coal Mining and Coal Processing

Dumps from coal mining and coal processing were developed in four generations. The first generation was a so called “Steep Slope” (Spitzkegelhalde) (Fig. 15). The second generation was a so called “Table Mountain” (Tafelberg) (Fig. 15). Common for both generations were the low quality of coal processing which causes in many cases a content of coal inside the waste dumps of more than 20%. Additionally, the material was tipped over the high edge which leads to a segregation of the waste. The coarse size stones built the bottom of the dumps covered by smaller sized material on the top. Oxygen could enter the dumps at the bottom (Fig. 16) and in combination with Pyrite this leads to high temperature and self-ignition of the coal.

Dump generations three and four were built with trucks without segregation of the material and compacted by trucks and dozers. The permeability for oxygen is very low. Additionally, the processing of coal became a higher quality and the content of coal inside the dumps became less than 7%. Self-ignition of hard coal needs a minimum content of coal of 11%.

This is the reason why only dumps of the first two generations burned in Germany. In one case more than 750° C were measured in a depth of only 5 m below the surface of the dump.

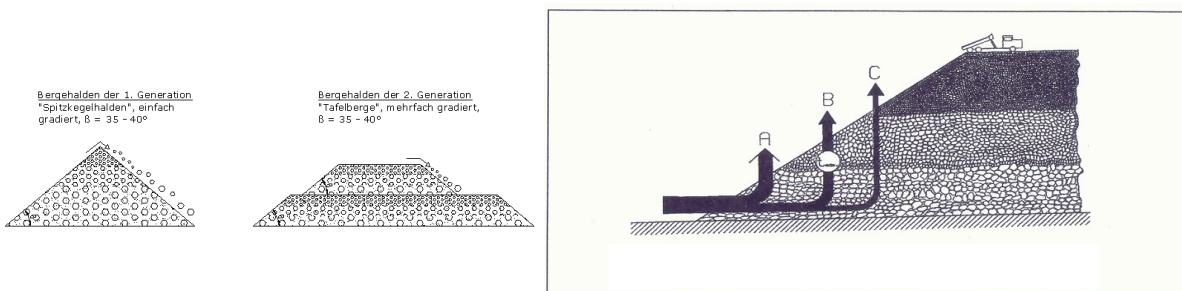


Fig. 15: Dumps of the first two generations
 Fir. 16: Oxygen entering a dump with segregated material

2.1.1. Firefighting with covering the burning Dump

Firefighting with water or inert gases like CO₂ or N₂ didn't stop the fire. Immediately after stopping the water or gas, burning started again. Only the stop of oxygen entering the dump stopped the fire. Therefore, dump Rheinelbe in Gelsenkirchen was covered with one million tons of soil on one slope and a gabion wall was constructed on another slope (Fig. 17 and 18).

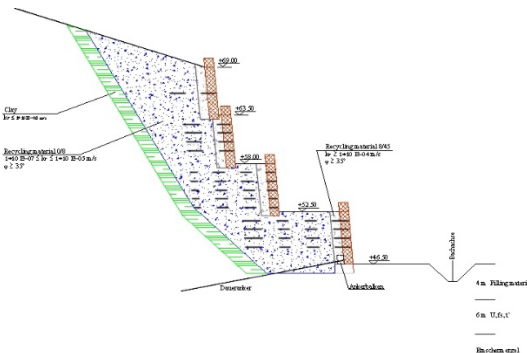


Fig. 17 and 18: Covering dump Rheinelbe with soil and gabion wall (own pictures)

2.1.2. Firefighting with Injection of Slurry

On dump Graf Moltke in Gladbeck was not enough space around the dump for covering with soil. In this case we decided to do the firefighting with an injection of a special slurry to install a fire wall inside the dump (Fig. 19 and 20). From special construction sites we got the waste from Jet Grouting. This is a mixture of water, cement and fine sized soil, mostly silt and clay.

In drill holes inside the dump special sleeve pipes were installed (Fig. 21). Every half meter, in some cases every third meter, the iron tubes had four holes with diameter one cm covered by a rubber sleeve. With a double case packer (Fig. 23), it was realized, that slurry was injected from the bottom to the top step by step with a pressure of 60 bars (Fig. 22). With this system a fire wall inside the dump was erected to stop the income of oxygen.

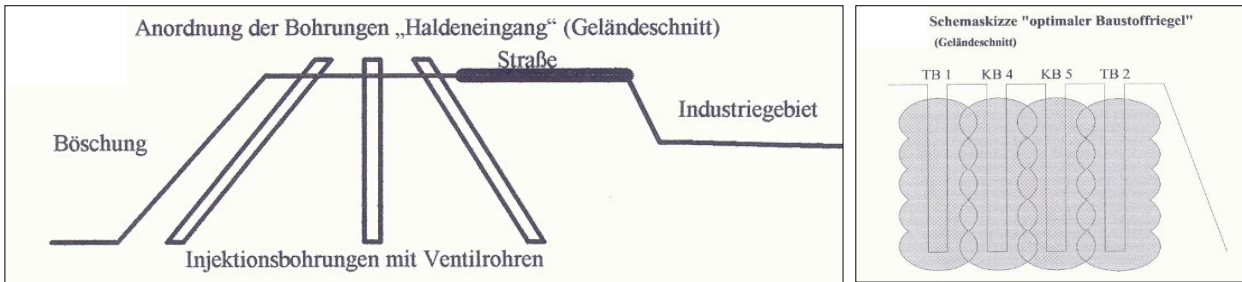


Fig. 19 and 20: Scheme of injection tubes (own pictures)

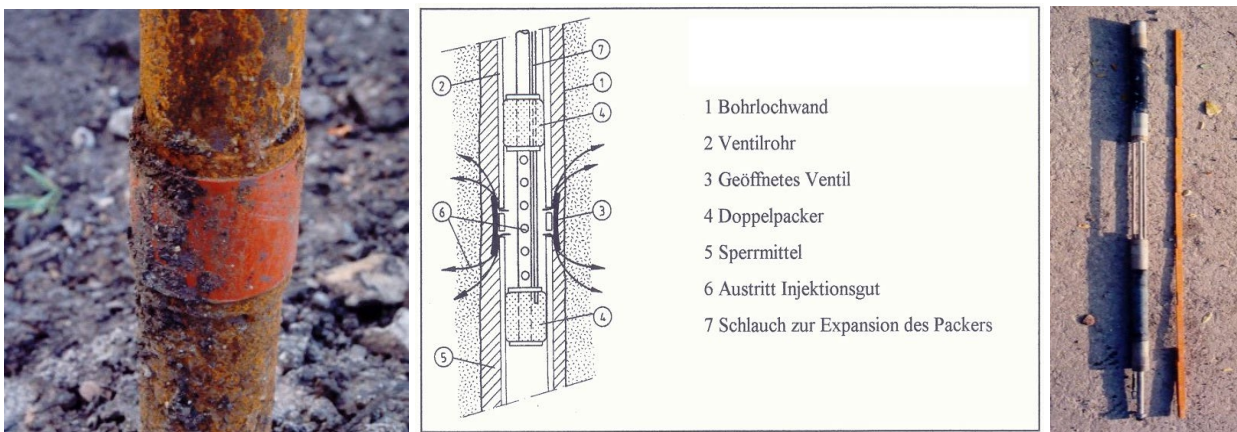


Fig. 21: Sleeve pipe (own picture)

Fig. 22: System with sleeve pipe and double case packer (own picture)

Fig. 23: Double case packer (own picture)

2.2. Firefighting of burning Coal Seams

The only way to stop the fire inside a burning coal seam, hard coal or brown coal, is to erect a fire wall inside the seam.

In a first step a good mapping is needed: The topography is important for planning the places where the drilling equipment can be placed, the dipping of the coal seams must be known for calculating the deep of the drillholes and the knowledge about the overburden (sandstone, siltstone or claystone) is useful.

In a second step lines of holes must be drilled in a safe distance to the fire front. Sleeve pipes should be cemented in these holes.

In the third step slurry should be pressed with more than 60 bars into the underground to erect a fire wall. To minimize the costs for the slurry, I suggest for Soma as an example to proof a mixture consisting fly ashes from the local power plant and water. Here some laboratory tests are necessary to find a flowable mixture with enough strength after hardening.

In a fourth step a monitoring system should be installed with drill holes behind the fire wall in the underground. Here the development of temperature and the content of gas should be measured. A rising concentration of

Carbon Hydrogen, for example Methane, is a sign for a coming fire because a fire in a coal seam works like a cookery. If there is a rising amount of CO₂ without Carbon Hydrogen it is a sign that the fire has passed.

2.3. Stabilization of Openings to Surface

To avoid sudden sinkholes on the surface caused by collapsing shaft fillings, a lot of work is necessary to secure these abandoned shafts. With more than 20,000 abandoned shafts from coal mining only in Ruhr Area it is a very expansive task which takes a lot of time.

2.3.1. Stabilization with Concrete

If the exact position of an abandoned shaft is known, it is possible to drill holes into the filling of the shaft from beside and press concrete into its filling. With this system the filling of the shaft is stabilized at its top, maybe up to twenty or fifty meters.

This stabilization with concrete is the best method for longtime stability. But it needs knowledge about the exact position of the former shaft and is very expensive. And it needs time.

2.3.2. Secure with Geogrids

The exact position of abandoned shafts filled with soil more than 50 years ago often is unknown. Existing maps show a position sometimes in a circle with radius up to 15 m (Fig. 24 and 25). In such a case it is impossible to secure the shaft filling with concrete pressed into drillholes from beside. Here it is necessary to secure the former shaft against accidents and sudden openings at the surface.



Fig. 24: Area of the abandoned shafts in Recreation area Botanical Garden Rombergpark Dortmund (Diplom thesis Annika Lining)

Fig. 25: Chief mine surveyor Hermann Mühlenbeck pointing on an abandoned mine shaft in botanical garden Rombergpark Dortmund (own picture)

With the use of Geogrids, it is possible to secure the surface of abandoned shafts against accidents (Fig. 26). Therefore, the surface should be excavated in the area where the former shaft is located. Normal is minimum one meter depth. After that the Geogrid-Layer is to fix on this plane and covered with soil again. If a collapse of the filling of the shaft occurs, the Geogrid secures the surface and only a small subsidence shows the collapse in the underground. After this the exact position of the former shaft is visible and a final stabilization with concrete like describes above is possible and necessary.

With Geogrids it is possible to save money and to win time. Maybe the collapse of the shaft filling will occur in some days, in some years or never. The very expensive stabilization with concrete will be only necessary when the filling is collapsed.

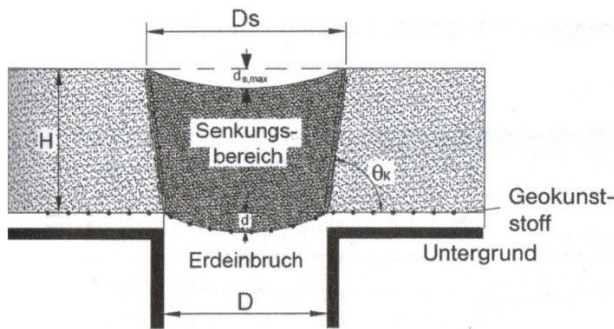


Fig. 26: Scheme and declaration of a filled shaft secured with geogrids (EBGEO, 2010)

2.4. Management of subsided Areas

Looking on subsided areas in different countries, I found three opportunities to deal with this aspect. In China, Province Jiangsu, they fill the subsided areas up to the former level of the landscape. If there is not enough material, they leave a lake below the natural groundwater table.

In Germany, especially in Ruhr Area, it is not common to fill subsided areas. It was a surprise to find a subsided area in the north part of Ruhr Area which was filled with mine waste, covered with soil and actual used for agriculture.

In Karaganda, Kazakhstan, big areas are in a filling process with waste from coal mining and processing.

Another way to deal with subsided areas is to do nothing. In China I found a lake in a subsided area with a surface of 100 km² and at that moment between six and ten meters deep. Other lakes in Province Jiangsu around Xuzhou are well designed like parks.

The deepest lake in a subsided area I found in Slovenia above Velenje brown coal mine. It is more than 100 meters deep now.

In Germany, especially in the Ruhr Area, one third of this area where more than four million people live, is below the natural groundwater table. In some parts the subsidence is more than 24 meters. Because of the inhabitants and the industry in that area, pumping of the groundwater is necessary.

2.4.1. Filling of subsided Areas

The filling of subsided areas causes a lot of new problems. Which material is available? How can the filled area be used in future?

Often the waste from coal mining and coal processing is available and used to fill up subsided areas. This material is available and cheap. But it contains in most cases about Sulphur and heavy metals. In contact with water, groundwater or rain, Sulphur Acid leaches the heavy metals and contaminates the groundwater. In China, Province Jiangsu around Xuzhou, minimum one meter of clay should cover the mine waste and prepare the area for agriculture use.

2.4.2. Lakes in subsided Areas

If there is not enough material available to fill up subsided areas, sometimes, especially in some Chinese regions, the surface of an area will sink below the natural groundwater table. These areas will be flooded and lakes dominate the landscape. In such cases it is important to take out all things which may contaminate the water in the future lakes.

Near to cities like Xuzhou, Province Jiangsu in China, it is possible to create parks around the lakes caused by underground mining.

2.4.3. Pumping of Groundwater in poldered Areas

In Germany, especially in Ruhr District, nearly one third of the area is now below the natural groundwater table. In some cases, the surface is now 24 meters deeper than before mining. But in this area live more than

four million people and many industrial sites are located there. Filling up these areas or to flood it is not possible.

The groundwater management in Ruhr District consists about 160 pumping stations (Fig. 27) which pump the groundwater from horizontal drainage systems into the next small river like Emscher (Fig. 28). Pumping round about 100 million cubic meters of water per year causes costs about 80 to 100 million Euro per year.



Fig. 27: In Ruhr Area exist about 160 pumping stations like in the picture. Without pumping the water table will rise up to 7 meters above the dyke (own picture).

Fig. 28: With three tubes the groundwater is lifted above the dyke (own picture)

2.5. Mine-Water Management

Mine water in Germany is high mineralized. To avoid a contact between mineralized mine water in the depth and fresh groundwater in upper layers, the mine water is pumped in some former shafts into the river Rhine. Amount of water and costs are similar to the groundwater management: 100 million cubic meters for around 100 million Euro per year.

2.6. Acid Mine Drainage (AMD) and Collapse of Roof-and-Pillar Mining

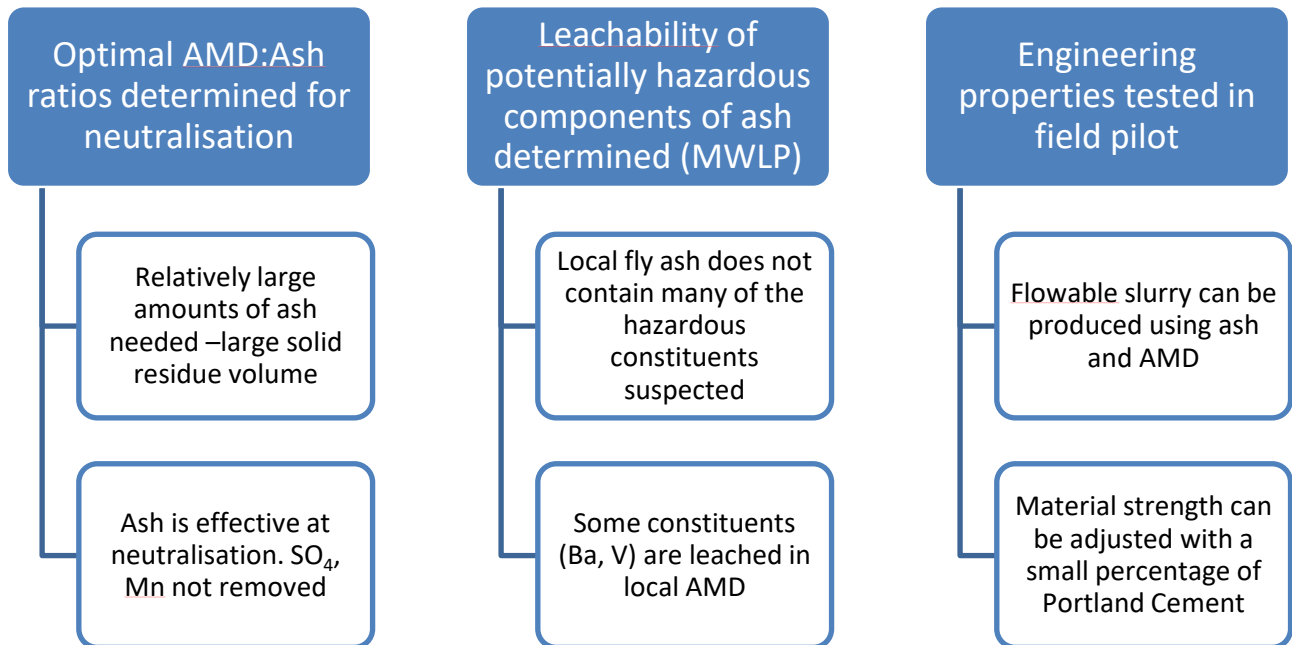
In Province Mpumalanga, South Africa, AMD from abandoned coal galleries is a serious problem (Fig. 11 and 12). Here it is combined with instable room-and-pillar mining (Fig. 13 and 14). With a low-cost system using fly ashes from power plants in that region both problems can be solved. First tests were done to proof the stability of the material after hardening (Fig. 29). Similar tests were done in laboratory of THGA (Technische Hochschule Georg Agricola) in Bochum, Germany. The results show, it is possible to stabilize the pillars and roofs to avoid sinkholes.



Fig. 29: Test field with a slurry with fly ashes from power plants (Henk Coetzee, Geological Survey of South Africa)

The slurry from fly ashes mixed with AMD has a high pH and is able to neutralize the low pH of AMD. Additionally, the new surfaces on coal pillars and surrounding sandstone, bottom and roof of mined seams, is covered with this slurry. Sulphur will not get in contact with oxygen and will not leach as Sulphur Acid.

Table 1: Results from testing slurries with local fly ashes from power plants (Henk Coetzee, Geological Survey of South Africa)



3. Results and Discussion

One very critical point in areas with coal mining or in postmining areas are the costs. With innovative solutions it is possible to repair damages caused by coal mining and processing. It is necessary to give inhabitants a save area.

Fly ashes from power plants are available and less expensive than cement. In other fields modern elements like geosynthetics help to reduce the costs.

4. Conclusion

The most important task in areas with running or abandoned coal mining is a save environment with stable ground, clean water and fresh air. With geotechnical solutions it is possible to stabilize ground against sink-holes above abandoned shafts or room-and pillar mining. Acid Mine Drainage (AMD) can be stopped. The firefighting on burning dumps and in burning coal seams is important to reduce air pollution.

Other damages or problems we had to solve are very special and not in this paper. In 2004 for example we had to solve the problem of acceleration of Methane inside cellars of houses. Since that time in cities Bochum and Dortmund, Ruhr District Germany, it is only allowed to build new houses if it is proofed that there is no Methane or the houses are protected against entering of Methane into cellars. To reduce the costs of this protection we developed a system with geosynthetics.

Other tasks are the stability of dumps and tailings in times of climate changes. It is necessary to proof if dumps and tailings will be save in a very strong rain event.

Acknowledgements

Most of the above works were done together with engineers and researchers from different companies and institutes. In South Africa for example it was the good relationship to Henk Coetzee from the Geological Survey in Pretoria.

In Germany I worked together with Professor Dr. Lutz-H. Benner and producers of geosynthetics. The Mine Authority of North Rhine-Westphalia helped us to develop new solutions for the firefighting on dumps.

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Reclamation Plan for EÜAŞ's Mining Areas After Mining Operations

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Abstract

EÜAŞ carries out electricity generation, wholesale trade, and electricity procurement activities on behalf of the public. It conducts the operation, maintenance, repair, rehabilitation, and modernization of its power generation facilities and mining areas. Additionally, it carries out the necessary technical work to make the mining sites under its legal license available for investment.

The regulation and ecological restoration of decommissioned coal mining sites are integral parts of mining activities. In this context, reforestation activities began in 1987 at the Kışlaköy Mine of the Afşin-Elbistan Lignite Basin owned by EÜAŞ, following the completion of mining operations. A restoration plan covering the period from 2011 to 2044 was prepared for this area. Afforestation efforts aimed at restoring the excavation and dumping areas of the South Aegean Lignite and Yeniköy Lignite Enterprises, licensed to EÜAŞ, started in 1991 following the conclusion of mining activities.

In this study, information will be provided about the afforestation activities carried out in the licensed areas of EÜAŞ.

Keywords: Lignite, Rehabilitation, Afforestation Activities

1. Introduction

More than a quarter of the world's energy demand and approximately 40% of electricity production are met by coal. It is estimated that the known coal reserves will be sufficient for more than 200 years, based on the 1990 production data. This duration is approximately four times longer than the period estimated for natural gas or oil. Even for countries without fossil fuel reserves, coal imports are considered safer than oil or natural gas imports due to the wide availability resulting from its broad geographical distribution worldwide. For these reasons, the dominance of coal in electricity production is expected to continue increasing (Çakıroğlu 2001).

The Afşin-Elbistan Lignite Basin, which holds the largest potential among our country's lignite deposits, spans an area of 120 km² between the districts of Afşin and Elbistan in Kahramanmaraş province. Our Kışlaköy Open Pit Mining Operation covers an area of 28 km² and is situated at approximately 1150 meters above sea level.

The initial studies in the Afşin-Elbistan Basin began in 1966 through German technical assistance, in collaboration with the German company Otto Gold GmbH and the Mineral Research and Exploration Institute (MTA). As a result of systematic drilling, the first Lignite Deposit was discovered in 1967. Feasibility reports for the basin were prepared in 1969-1970, and investment activities commenced in 1973.

As a result of the studies and explorations conducted throughout the basin, 4.3 billion tons of proved reserves and 3.4 billion tons of mineable reserves were identified. These reserves consist of three main sectors named Kışlaköy, Afşin, and Çöllolar, along with their extensions. The Kışlaköy Open Pit, known as the Afşin-Elbistan (A) Project, represents the first open-pit operation of the basin, and it was determined that this area contained approximately 582 million tons of lignite reserves as of May 1984.

In the integrated project initiated by the Turkish Electricity Administration (TEK), the mining section was separated in 1972 and transferred to the Turkish Coal Enterprises (TKİ). TKİ began its operations as the

Facility Directorate on 21.03.1972, and due to the expansion of its activities, the Facility Directorate was upgraded to the Institution Directorate on 07.04.1975.

The institution was established to evaluate the existing lignite assets of TKİ Institution in the licensed areas it owns and will own in the South-East Anatolia Afşin-Elbistan Lignite Basin, to construct and operate the facilities that constitute the mining part of the Afşin-Elbistan Integrated Project and that will operate according to the production programs, to provide required amount of the fuel necessary for energy production of the thermal power plant and to cooperate with TEK for this purpose, to establish facilities that will produce domestic fuel coal (which will provide dry coal or similar production opportunities) by utilizing low-calorie lignite and to carry out technological, economic, commercial, legal and social activities related to these issues.

The institution was connected to the General Directorate of the Turkish Electricity Production and Transmission Corporation on 06.02.1995 and transformed into an Operation Directorate. The institution was connected to the General Directorate of the Electricity Production Corporation (EÜAŞ), which was established on 01.10.2001 with the division of TEAŞ into three, and continued its activities until 30.11.2018 and has been continuing as the Afşin-Elbistan Lignite Control, Coordination and Operation Directorate since this transfer date.

As for the Yatağan and Milas Fields, with the Privatization High Council decision dated 19.02.2015 and numbered 2015/124 and the High Planning Council decision dated 30.07.2015 and numbered 2015/T-14, all remaining assets of our subsidiaries YEAŞ and KEAŞ General Directorates and the licenses covering the mining areas were transferred to the EÜAŞ General Directorate.

2. Reclamation

Reclamation refers to the rehabilitation of areas whose topography has changed during or as a result of mining exploration and operation activities, ensuring environmental safety and conforming to the project, and making them compatible with the environment as specified in the relevant legislation.

It is a project that involves the restoration of lands, sites, and areas degraded due to the activities of investors, operational processes, and entrepreneurs. The project includes ensuring biological sensitivity, carrying out necessary corrective measures, spreading plant soil, planting vegetation, sowing seeds, creating recreational areas based on the characteristic features of the land structure, and preparing the necessary landscaping (vegetation and afforestation) processes within a planned framework.

According to the Regulation on the Reclamation of Lands Degraded by Mining Activities, issued by the Ministry of Environment, Urbanization, and Climate Change in December 2007 and revised on January 23, 2010 with the number 27471, obligations have been made mandatory to eliminate the damages caused by mining activities in forest and non-forest areas and to ensure the rehabilitation of abandoned sites.

In mining activities conducted outside areas classified as forests, operators are required, in addition to obtaining Environmental Impact Assessment (EIA) permits of all scopes, to prepare a Reclamation Plan/Environmental Management Plan (for minerals such as sand, gravel, etc.) and to commit to implementing this plan exactly as submitted to the relevant authorities.

Operators who have obtained the operation permit are required to submit a "Reclamation Plan" to the Provincial Directorate of Environment, Urbanization, and Climate Change within 1 year at the latest. In forested areas, it has become mandatory for operators applying for a forest operation permit to prepare a rehabilitation project. Additionally, for operators who were active before this Regulation came into force and have not submitted a reclamation plan, the reclamation format shall be prepared by the institutions and organizations authorized to prepare an Environmental Impact Assessment report or project introduction file.

3. Phases of the Reclamation Plan

- a) Determining the current status before the activity by considering the flora, fauna, soil, water, air, natural and cultural landscape values, geological conditions, geomorphological and hydrogeological factors, geological risks, as well as socio-economic and cultural factors in the activity area and its surroundings.
- b) Ensuring the physical, chemical, and geological stability of the activity area.
- c) Rearrangement of the activity area.
- ç) Implementation of soil, water, and air management practices.
- d) Execution of landscaping works.
- e) Improvement of the activity areas.
- f) Closure and abandonment of the activity areas.
- g) Implementation of monitoring and inspection methods.

After the box-cut was opened for mining activities in the Kışlaköy Lignite Mine site, the extracted overburden material was deposited in the designated external dumping area. Additionally, a reclamation plan covering the period from 2011 to 2044 was prepared. In this context, approximately 743,285 trees of species including Cedar, Black Pine, Acacia, Mahaleb, Maple, Ash, Pagoda Tree, False Acacia, Blue Spruce, Melye, Juniper, Plane Tree, and Oleaster were planted on an area of about 907.6 hectares in the external dumping area of the Kışlaköy Lignite Mine.

Afforestation activities aimed at the reclamation of the excavation and dumping areas in the South Aegean Lignite and Yeniköy Lignite Enterprises started in 1991 following mining operations. Species such as Acacia, Stone Pine, and Black Cypress were planted in the external dumping areas, while Olive trees, which are the most widespread and economically valuable in the region, were planted in the internal dumping areas. In the afforested areas, wildlife is rapidly developing, and the reclamation of nature is largely achieved. Between 1991 and 2012, a total of 1,940,504 trees were planted over an area of 1,081 hectares by the General Directorate of TKİ in GELİ and YLİ (Muğla-Yatağan and Yeniköy).

In Yatağan-Eskihisar and Milas-Karacağağaç, the olives from the olive trees are harvested annually by the EÜAŞ General Directorate and processed into olive oil at the Agricultural Sales Cooperative. The extra virgin olive oil used in the EÜAŞ General Directorate Cafeteria is produced from Gemlik variety trees located on 550 acres of land in the Milas and Yatağan regions of Muğla Province, affiliated with EÜAŞ. In 2023, a total of 31,150 kg of olives were harvested, yielding 5,729 kg of olive oil. The tree species planted in the reclaimed mining sites of the South Aegean Lignite Operation and Yeniköy Lignite Operation include Acacia, Ailanthus, Olive, Ash, Maple, Black Cypress, Ligustrum, and Stone Pine.

4. Conclusion

Afforestation activities have been conducted in the areas where dumping operations were completed at the external dumping site of the Kışlaköy Lignite Mine in Kahramanmaraş. The areas where afforestation has been completed have been transferred to the Regional Directorate of Forestry. In the external dumping areas of Muğla, species such as Acacia, Stone Pine, and Black Cypress were planted, while Olive trees, which are the most widespread and economically valuable in the region, were planted in the internal dumping areas. In the afforested areas, reclamation to nature has been largely achieved. As EÜAŞ, reclamation planning will continue in areas where mining activities have been completed.

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Kurşun, Çinko ve Bakır Zenginleştirme Tesisi Ekolojik Temelli Rehabilitasyonu

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Özet

Madencilik faaliyetlerinin sona ermesiyle maden sahalarının güvenli, çevresel açıdan sürdürülebilir ve uzun vadeli arazi kullanımını destekleyerek doğaya kazandırılması, modern madencilik yaklaşımlarının temel ilkeleri arasında yer almaktadır. Güncel uluslararası yaklaşımlar, maden sahası kapatımının yalnızca teknik risklerin ortadan kaldırılmasına yönelik bir süreç değil; çevresel rehabilitasyon, ekosistem bütünlüğü ve sosyo-ekonomik dönüşümü içeren çok boyutlu planlama faaliyeti olarak ele alınması gerektiğini ortaya koymaktadır. Bu çalışma, Çanakkale ili Lapseki ilçesi Umurbey/Karaömerler köyü sınırlarında bulunan kurşun, çinko ve bakır zenginleştirme tesisine ait maden sahasında gerçekleştirilen bütüncül kapatma ve rehabilitasyon uygulamalarını değerlendirerek, söz konusu uygulamayı uluslararası iyi uygulamalar çerçevesinde tartışmaktadır.

Çalışmalar kapsamında, sahada bulunan atık barajları, mühendislik esasları ve mevzuat gerekliliklerine uygun olarak kapatılmış, tesis ve tüm yardımcı yapılar sökülerek alan doğal topoğrafya ile uyumlu hale getirilmiştir. Rehabilitasyon sürecinde drenaj sistemlerinin inşası, bitkisel toprak serimi ve yüzey stabilizasyonu gerçekleştirilmiş, bitkisel toprağın besin içerikleriyle zenginleştirilmesi ve yerel türlerle bitkilendirme aşamasına geçilmiştir. Kullanılacak bitki türleri; ekolojik uyum, kuraklığa dayanıklılık ve ekonomik fayda kriterleri göz önünde bulundurularak seçilmiştir. Uygulanan rehabilitasyon yaklaşımının yalnızca çevresel riskleri azaltmakla kalmayıp, aynı zamanda ekosistem fonksiyonlarını yeniden kazandırdığı ve alanın sürdürülebilir kullanımına katkı sağlayacağı öngörülmektedir. Bu çalışma, Türkiye'de madencilik sonrası arazi yönetimi açısından iyi bir uygulama örneği sunmakta ve uluslararası madencilik sonrası rehabilitasyon literatürüne katkı sağlamaktadır.

Anahtar Kelimeler: Madencilik sonrası rehabilitasyon, ekolojik restorasyon, toprak ıslahı, biyoçeşitlilik, ekosistem temelli rehabilitasyon, sürdürülebilir arazi kullanımı

Abstract

The closure and rehabilitation of mine sites following the cessation of mining activities constitute a fundamental principle of modern mining, aiming to ensure safety, environmental sustainability, and long-term land use. Contemporary international approaches recognize mine closure not merely as a technical risk mitigation process, but as a multidimensional framework integrating environmental rehabilitation, ecosystem integrity, and socio-economic transition.

This study evaluates the integrated closure and ecological rehabilitation practices implemented at a former lead, zinc, and copper mine site and processing facility located in Umurbey/Karaömerler, Lapseki (Çanakkale, Türkiye), and discusses the approach within the framework of international best practices. Tailings storage facilities were closed in accordance with engineering principles and regulatory requirements, and all plant infrastructure and auxiliary units were dismantled to ensure compatibility with the natural topography. Rehabilitation measures included drainage construction, topsoil placement, surface stabilization, soil amendment, and revegetation using locally adapted species selected based on ecological compatibility, drought tolerance, and economic value.

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The ecosystem-based rehabilitation approach is expected to reduce environmental risks, restore ecosystem functions, and support sustainable land use, while providing a representative case for post-mining rehabilitation practices in Türkiye.

Keywords: Post-mining rehabilitation, ecological restoration, ecosystem-based rehabilitation, soil amelioration, revegetation, biodiversity restoration, sustainable land use

1. Giriş

Madencilik faaliyetleri, doğal kaynakların ekonomik olarak değerlendirilmesini sağlarken, faaliyetlerin sona ermesiyle birlikte önemli çevresel yükümlülükleri de beraberinde getirmektedir. Madencilik faaliyetleri, (maden çıkarma süreçleri, cevher zenginleştirme süreçleri ve maden atığı depolama süreçleri) mikro ölçeklerde ekosistem yapısını bozarak topografyayı, toprak özelliklerini, su döngüsünü ve biyolojik çeşitliliği olumsuz etkileyebilmektedir. Bu bağlamda, maden sahalarının kapatılması ve rehabilitasyonu, yalnızca fiziksel güvenliğin sağlanması ve görsel etkilerin ortadan kaldırılması değil, aynı zamanda bozulan ekosistemlerin yeniden işlevsel hale getirilmesini kapsayan çok boyutlu bir süreçtir.

Son yıllarda, geleneksel mühendislik odaklı ve sadece ağaçlandırmaya dayalı kapatma yaklaşımlarının yerini, ekosistem temelli rehabilitasyon anlayışı almaktadır. Bu yaklaşım, doğal süreçlerle uyumlu, biyolojik çeşitliliği destekleyen ve sosyal açıdan yerel topluluklara ekonomik getirisi de olan uzun vadeli sürdürülebilirliği hedefleyen uygulamaları içermektedir. Madencilik sonrası alanların restorasyonu, yalnızca fiziksel ve kimyasal iyileştirmeleri değil, aynı zamanda toprak biyotasının yeniden tesisini, bitki örtüsü süksesyonunun başlatılmasını ve fauna geri dönüşünün desteklenmesini gerektiren bütüncül bir anlayışı zorunlu kılmaktadır.

Bu çalışmanın amacı, Çanakkale Lapseki Umurbey/Karaömerler köyü'nde yer alan kurşun, çinko ve bakır zenginleştirme tesisinde uygulanan ekolojik temelli rehabilitasyon sürecini ortaya koymak, kullanılan yöntemleri toprak iyileştirme, bitkilendirme ve biyoçeşitlilik restorasyonu bileşenleri çerçevesinde değerlendirmek ve elde edilen sonuçları güncel literatür ışığında tartışmaktır.

2. Materyal ve Metot

2.1. Çalışma Alanı

Çalışma alanı, Çanakkale ili Lapseki ilçesine bağlı Umurbey/Karaömerler köyü'nde yer alan ekonomik ömrünü tamamlamış kurşun, çinko ve bakır madeni ve zenginleştirme tesisi'nin bulunduğu alandır. Ekolojik restorasyona konu faaliyet alanı cevher zenginleştirme tesisi, güney maden atığı depolama tesisi ve kuzey maden atığı depolama tesisinden oluşmaktadır. Tüm faaliyet alanı yükselti değerleri 139-705 m arasında değişmekte olup; Cevher zenginleştirme tesisi ve güney maden atığı depolama tesisi 255-320 m kotlarında, kuzey maden atığı depolama tesisi ise 490-500 metre kotları arasında yer almaktadır. Bu durum, alan içinde heterojen topografik koşulların hâkim olduğunu göstermektedir.

Saha 35 yıla yakın bir süre zarfında, kurşun, çinko ve bakır zenginleştirme tesisine ev sahipliği yapmış olup, işletme faaliyetlerinin tamamlanmasının ardından kapatma ve rehabilitasyon süreci başlatılmıştır. Proje kapsamında yaklaşık 5 hektar alanda -kazı alanları, pasa döküm sahaları, cevher zenginleştirme tesisi ve maden atığı depolama tesisi bulunmaktadır. İşletme sonrası ekonomik ömrünü tamamlayan cevher zenginleştirme tesisi dahil tüm alanlarda ekolojik rehabilitasyon çalışmalarına başlanılmıştır.

2.2. Rehabilitasyon Yaklaşımı

Proje kapsamında geliştirilen rehabilitasyon yaklaşımı, Çevre Mevzuatı kapsamında ve uluslararası literatürde önerilen bütüncül restorasyon prensipleriyle uyumlu olarak tasarlanmıştır.

Çevre Mevzuatı kapsamında; cevher zenginleştirme tesisi, güney maden atığı depolama tesisi ve kuzey maden atığı depolama tesisini kapsayacak şekilde Maden Atıkları Yönetmeliği gerekliliklerine uygun olarak kapatma planı hazırlanmış ve Çevre, Şehircilik ve İklim Değişikliği Bakanlığınca onaylanmıştır. Maden Atıkları Yönetmeliğince Kapatma Planı yedi temel bileşenden oluşmaktadır.

1. Kapatma projesi hazırlanması ve onayı
2. Atık depolama faaliyetinin tamamen sona ermesi

3. Susuzlaştırma / kurutma
4. Tesviye ve tampon tabaka serimi
5. Stabilite kontrolü
6. Yağmur suyu drenaj kanalları
7. Geçirimsiz üst örtü sistemi

Cevher zenginleştirme tesisi ve maden atıkları depolama alanlarını kapsayan kapatma planı ile; depolama tesisinin stabil hale getirilmesi, infiltrasyonun azaltılması, yağmur sularının drenajının sağlanması işlemleri Su Yapıları Denetim Firması gözetiminde tamamlanmış ve denetim raporları Bakanlığa sunulularak nihai onay alınmıştır. Böylelikle kapatılan alanlarda çevre ve insan sağlığına zarar vermeyecek nihai yapı elde edilmiştir.

Kapatma planına uygun şekilde oluşturulan nihai yapı, uluslararası literatürde önerilen bütüncül restorasyon prensipleriyle uyumlu olarak, dört temel bileşen üzerine oluşturulmuştur.

1. Toprağın fiziksel, kimyasal ve biyolojik iyileştirilmesi,
2. Yerel ve yüksek adaptasyon kabiliyetine sahip bitki türlerinin kullanılması,
3. Fauna/entomofauna çeşitliliğinin yeniden oluşmasının desteklenmesi,
4. Erozyon ve yüzey akışının kontrol altına alınması.

Bu bileşenler, ekolojik süksesyonun doğal aşamalarını temel alan ve uygulama-izleme-geri besleme döngüsü ile ilerleyen 48 aylık bütünlük bir zaman planı çerçevesinde yürütülecektir.

2.3. Toprak İyileştirme Teknikleri

Madencilik faaliyetleri sonucunda fiziksel ve kimyasal yapısı bozulan toprakların iyileştirilmesi, rehabilitasyon sürecinin temel önceliklerinden birini oluşturmaktadır. Bu kapsamda, sahada aşağıdaki toprak iyileştirme uygulamaları gerçekleştirilecektir:

Tablo 1: Toprak İyileştirme İşlem Adımları

İşlem Adımı	Uygulama	Amaç	Beklenen Çıktı
Organik madde uygulaması	Kompost, iyi yanmış çiftlik gübresi, odun yongası toprağa homojen karıştırma	Toprak karbon içeriğini artırmak ve biyolojik aktiviteyi başlatmak	Organik maddece zenginleştirilmiş rehabilitasyon toprağı
pH düzenlemesi	Asidik topraklarda kireç taşı (CaCO ₃) veya dolomit uygulaması; alkali topraklarda kükürt uygulaması	Kök gelişimine uygun kimyasal ortam oluşturmak	Dengelenmiş toprak pH değeri (6.0-7.5 aralığı)
Mikrobiyal aşılama	PGPR bakterileri ve mikoriza uygulaması	Azot fiksasyonu ve besin yararırlılığını artırmak	Aktif rizosfer mikrobiyal topluluğu
Besin dengesi sağlanması	Organomineral gübre ve mikro element (Zn, Fe) takviyesi	Bitki gelişimi için minimum besin eşliğini sağlamak	Dengeli besin içeriğine sahip toprak
Malçlama	Saman, kuru ot, biyobozunur yüzey materyalleri	Yüzey erozyonunu azaltmak, nemi korumak, organik madde sağlamak	Stabilize yüzey ve gelişmiş toprak nemi

Literatürde, maden atık alanlarında organik madde uygulamalarının; toprağın su tutma kapasitesini, infiltrasyonunu ve mikroorganizma faaliyetini belirgin şekilde artırdığı, pH düzenlemesinin ise ağır metallerin hareketliliğini azaltarak bitkide birikme riskini düşürdüğü bildirilmektedir. Ayrıca, mikrobiyal aşılama uygulamalarının özellikle fakir topraklarda bitki tutma başarısını ve besin alımını önemli ölçüde iyileştirdiği çeşitli çalışmalarda vurgulanmaktadır.

2.4. Bitkilendirme ve Vejetasyon Restorasyonu

Bitkilendirme aşamasında, bölgenin doğal vejetasyon yapısı dikkate alınarak yerel ve ekolojik uyumu yüksek türler seçilmiştir. Tür seçiminde iklim ve toprak koşullarına uyum, kök sisteminin toprak stabilitesine katkısı, toprak örtücülük kapasitesi, azot fiksasyonu ve organik madde birikimine katkı ile fauna için besin ve habitat oluşturma potansiyeli gibi ölçütler esas alınmıştır. Rehabilitasyon süreci, ekolojik süksesyonun doğal aşamalarını takip eden dört yıllık bir bitkilendirme planı çerçevesinde yürütülecektir.

Tablo 2: Dört Yıllık Bitkilendirme ve Rehabilitasyon Fazları

Yıl / Faz	Ana Amaç	Önerilen Tür Grupları	Uygulama Notları
1. Yıl - Öncü Faz	Erozyonu durdurmak, yüzeyi hızlı örtmek, toprağı organik madde ve azotça zenginleştirmek	<i>Trifolium pratense/repens, Medicago sativa, Lotus corniculatus, Festuca spp., Lolium perenne</i>	Hidrotohumlama veya yaygın serpmek ekim; Rhizobium aşılması önerilir
2. Yıl - Mera ve Örtü Güçlendirme Fazı	Çok yıllık otsu örtüyü güçlendirmek, toprak biyolojisini desteklemek	İlk yıl türleri + <i>Dactylis glomerata, Bromus spp.</i> , ilave baklagiller	Over-seeding; ilk 2-3 yıl otlatmadan kaçınılmalıdır
3. Yıl - Ağaç ve Çalı Formasyonu	Uzun vadeli odunsu vejetasyon iskeletini oluşturmak	<i>Pinus brutia, Quercus pubescens, Q. coccifera, Pyrus amygdaliformis, Arbutus andrachne, Spartium junceum, Rosa canina</i>	Sonbahar-ilkbahar fidan dikimi; şevlerde kademeli yerleşim ve can suyu desteğı
4. Yıl - Bakım, İzleme ve Takviye Dikimleri	Eksik alanların tamamlanması, türlerin gelişiminin izlenmesi	Tüm tür grupları	Fidan tamamlama, çalı şekillendirme, ilave mera tohumu, yıllık flora-fauna raporları

Uluslararası literatürde, maden sahalarının rehabilitasyonunda öncü türlerin kullanımının toprak iyileşmesini hızlandırdığı ve ardından gelecek klimaks türler için uygun mikrohabitat hazırladığı vurgulanmaktadır. Özellikle baklagil türlerinin azot fiksasyonu kapasitesi sayesinde toprak verimliliğini artırdığı ve mikrobiyal aktiviteyi uyardığı bilinmektedir.

Tablo 3: Tozlayıcı (Polinatör) Dostu Bitki Türleri ve Ekolojik Fonksiyonları

Bilimsel Adı	Türkçe Adı	Çiçeklenme Dönemi	Ekolojik Fonksiyon / Hedef Böcek Grupları
<i>Trifolium pratense/repens</i>	Kırmızı/Beyaz üçgül	İlkbahar-Yaz	Arılar ve bombuslar için yüksek nektar-pol kaynağı
<i>Medicago sativa</i>	Yonca	İlkbahar-Yaz	Arı aktivitesini artırır; mera + polinatör bitkisi
<i>Lotus corniculatus</i>	Gazal boynuzu	İlkbahar-Sonbahar	Küçük tozlayıcılar ve yaban arıları için kritik
<i>Salvia fruticosa/verbenaca</i>	Adaçayı türleri	İlkbahar-Yaz	Kelebek ve yaban arılarının yoğun ziyaret ettiği türler
<i>Rosmarinus officinalis</i>	Biberiye	Kış sonu-İlkbahar	Erken dönem polinatörlerini destekler
<i>Rosa canina</i>	Kuşburnu	İlkbahar (çiçek), Sonbahar (meyve)	Polinatör + kuş faunası için çift işlev
<i>Arbutus andrachne</i>	Sandal	Sonbahar-Kış	Geç dönem polinatörleri destekleyen az sayıdaki türlerden

Polinatör dostu türlerin rehabilitasyon planlarına entegre edilmesi, yalnızca biyoçeşitliliği artırmakla kalmayıp, aynı zamanda ekosistemin işlevsel bütünlüğünü yeniden kurmaya yönelik temel bir restorasyon bileşeni olarak değerlendirilmektedir.

2.5. Erozyon Kontrolü

Eğimli arazilerde yüzey akışının kontrol altına alınması ve toprak kayıplarının azaltılması amacıyla bitki örtüsü tesisine ek olarak mühendislik önlemleri de planlanmaktadır. Bu kapsamda:

- Yüzey şekillendirme ve drenaj sistemlerinin inşası,
- Şev stabilizasyonu için biyoteknik yöntemler (çalı demetleri, kazık kullanımı),
- Malçlama ve biyobozunur yüzey örtüleri,
- Rüzgâr erozyonunu azaltmak için rüzgâr kıran bitki şeritleri uygulanacaktır.

Literatürde, bitkisel örtünün kök sistemleri aracılığıyla toprağı stabilize ettiği ve yüzey erozyonunu önemli ölçüde azalttığı çok sayıda çalışmada gösterilmiştir.

2.6. Fauna Rehabilitasyonu ve İzleme

Proje kapsamında, rehabilitasyon sürecinde toprak ve bitki örtüsünün gelişimine bağlı olarak böcek çeşitliliğinde meydana gelen değişimi sistematik olarak izlemek üzere 48 aylık bir entomofauna izleme programlanmıştır. İzlenecek temel böcek grupları şunlardır:

- **Toprak faunası:** Karıncalar, toprak böcekleri (Carabidae), izopodlar, diplopodlar
- **Tozlayıcılar:** Arılar (Apoidea), kelebekler (Lepidoptera), sinekler (Diptera)
- **Fitofaj türler:** Yaprak böcekleri, çekirgeler
- **Predatör türler:** Örümcekler, uğur böcekleri, mantisler
- **Çürükçül türler:** Coleoptera (Scarabaeidae), sinek larvaları

Örnekleme yöntemleri arasında pitfall tuzakları, sarı yapışkan tuzaklar, pan tuzaklar, sweep net örnekleme, Malaise tuzakları ve ışık tuzakları yer almaktadır. Bu yöntemler, uluslararası ekolojik izleme protokolleriyle uyumludur.

Mikrohabitat çeşitliliğini artırmak amacıyla sahada ölü odun yığınları, taş istifleri, böcek otelleri ve polenektar kaynağı çiçekli bitki adaları oluşturulacaktır. Bu tür mikrohabitat yapılarının, böcek kolonizasyonunu hızlandırdığı ve tür çeşitliliğini artırdığı literatürde vurgulanmaktadır.

2.7. Uzaktan Algılama ve CBS Tabanlı İzleme

Rehabilitasyon uygulamalarının ekolojik etkilerinin zamansal ve mekânsal olarak izlenmesi amacıyla uzaktan algılama ve CBS tabanlı analizler planlanmıştır. Bu kapsamda:

- Landsat (1984-günümüz) ve Sentinel-2 (2015-günümüz) uydu görüntüleri kullanılarak NDVI (Normalize Edilmiş Bitki Fark İndeksi), SAVI (Toprak Ayarlı Bitki İndeksi), NDWI (Normalize Edilmiş Su Fark İndeksi) ve NDMI (Normalize Edilmiş Nem Fark İndeksi) hesaplanmıştır,
- Yılda iki dron uçuşu ile 4 cm çözünürlüklü ortofotolar elde edilmiştir,
- Arazi örtüsü ve kullanım haritaları oluşturulmuş,
- Erozyon riski ve bitki başarısı risk haritaları üretilmiştir.

Uzaktan algılama tekniklerinin maden rehabilitasyon sahalarının izlenmesinde etkin bir araç olduğu ve özellikle geniş alanlarda zamansal değişimlerin nesnel olarak değerlendirilmesine olanak sağladığı literatürde vurgulanmaktadır.

3. Bulgular ve Tartışma

3.1. Toprak İyileştirme Sonuçları

Uygulanan toprak iyileştirme çalışmaları sonucunda, rehabilitasyon alanında toprağın fiziksel, kimyasal ve biyolojik özelliklerinde belirgin iyileşmeler gözlenmiştir. Organik madde uygulamaları sayesinde toprağın su tutma kapasitesi, infiltrasyon hızı ve mikroorganizma faaliyeti artmış; pH düzenlemesi ile bitki gelişimi için uygun kimyasal ortam sağlanmıştır. Bu bulgular, maden atık alanlarında organik madde ve pH düzenleyici uygulamaların etkinliğini gösteren literatür bulgularıyla uyumludur.

Literatürde, maden atığı substratlarının genellikle düşük organik madde içeriği (%1'den az), yüksek hacim ağırlığı ve aşırı asidik veya alkali pH değerleri sergilediği bildirilmektedir. Bu çalışmada uygulanan organik madde takviyesi, kompost ve çiftlik gübresi uygulamaları ile toprağın organik karbon içeriğinin artırılması, mikrobiyal aktivitenin yeniden başlatılması açısından kritik önem taşımıştır.

Tablo 4: Toprak Sağlığı İzleme Parametreleri ve Hedef Değerler

Parametre	Başlangıç Değeri	Hedef Değer	İyileşme Göstergesi
Organik Madde (%)	<1.0	>2.0	OM artışı
pH	3.5-5.5 veya >8.5	6.0-7.5	Hedef aralığa yaklaşma
EC (tuzluluk)	>4 dS/m	<2 dS/m	EC azalması
Toplam Azot (N)	Düşük	Yeterli	N içeriğinde artış
Yarayışlı Fosfor (P)	Düşük	Yeterli	P içeriğinde artış
Mikrobiyal solunum	Düşük	Yüksek	CO ₂ salımında artış

3.2. Bitki Tutma ve Gelişim Performansı

Bitkilendirme çalışmaları başlatılmış olup, özellikle öncü türlerin (öncü faz) ve baklagil ağırlıklı karışımların ilk yılda yüksek çimlenme ve yüzey kaplama başarısı gösterdiği belirlenmiştir. Çok yıllık buğdaygil ve baklagil türlerinden oluşan mera karışımı ikinci yılda alanda baskın hale gelmesi beklenirken, üçüncü yılda tesis edilen ağaç ve çalı türlerinin tutma oranının %70'in üzerinde olacağı ön görülmektedir.

Tablo 5: Bitki Türlerinin Fonksiyonel Özelliklere Göre Sınıflandırılması

Fonksiyonel Grup	Örnek Türler	Ekolojik İşlev
Kuvvetli kök gelişimi gösteren türler	<i>Salix</i> spp., <i>Populus</i> spp., <i>Alnus</i> spp., <i>Carpinus betulus</i>	Şev stabilitesi, derin/yoğun kök sistemleri
İyi gövde gelişimi ve çalı formu oluşturan türler	<i>Crataegus monogyna</i> , <i>Rosa canina</i> , <i>Berberis vulgaris</i> , <i>Hippophae rhamnoides</i>	Görsel ve ekolojik bariyer, fauna için barınak ve besin kaynağı
Toprak örtücü ve yüzey koruyucu türler	<i>Symphoricarpos albus</i> , <i>Spiraea vanhouttei</i> , <i>Lonicera</i> spp.	Yüzey erozyonunu azaltma, toprak nemini koruma
Azot bağlayıcı türler	<i>Trifolium</i> spp., <i>Medicago</i> spp., <i>Lotus</i> spp., <i>Spartium junceum</i>	Toprak verimliliğini artırma, mikrobiyal aktiviteyi uyarma

3.3. Biyoçeşitlilik Geri Dönüşü

Entomofauna izleme çalışmaları, ilk tohumlama sonrası rehabilitasyon sürecinin ilerlemesiyle paralel olarak böcek çeşitliliğinde belirgin bir artış olduğunu göstermiştir. Özellikle tozlayıcı gruplar (Apoidea, Lepidoptera) ve toprak faunası (Carabidae) bolluğundaki artış, ilerleyen yıllarda habitat kalitesinin büyük oranda iyileşmeye yatkınlık göstergesi olarak değerlendirilmiştir. Mikrohabitat yapılarının (böcek otelleri, ölü odun yığınları, taş istifleri) kurulması, özellikle predatör ve çürükçül türlerin kolonizasyonunu hızlandıracağı ön görülmektedir..

Literatürde, restorasyon ekosistemlerinde tozlayıcı böcek popülasyonlarının yeniden tesisinde çiçekli bitki türlerinin kritik rol oynadığı vurgulanmaktadır. Bu çalışmada kullanılan polinatör dostu türlerin farklı mevsimlerde çiçeklenmesi, yıl boyunca tozlayıcılara süreklilik sağlayan bir çiçeklenme takvimi oluşturmuştur.

Tablo 6: Böcek Faunası İzleme Yöntemleri ve Hedef Gruplar

Yöntem	Hedef Böcek Grupları	Örnekleme Sıklığı
Pitfall (Pota) Tuzakları	Toprak yüzeyinde yürüyen böcekler (Carabidae, Formicidae, Staphylinidae)	Aylık
Sarı Yapışkan Tuzaklar	Uçan fitofaj ve tozlayıcı böcekler	Aylık
Pan Tuzaklar	Arı ve sinek çeşitliliği	İlkbahar-Yaz (6-8 saat)
Sweep Net (Süpürme Ağı)	Çalı ve otsu bitkilerde yaşayan türler	Mevsimlik
Malaise Tuzakları	Uçan böcekler (Diptera, Hymenoptera)	Yılda 2 kez
Işık Tuzakları (UV)	Gece aktif böcekler (Lepidoptera)	Yaz aylarında 3 gece
Berlese Hunisi	Toprak mikrofaunası (Collembola, akar)	Yılda 2 kez

3.4. Erozyon Kontrolü Başarısı

Rehabilitasyon uygulamaları sonucunda, alanda yüzey akışı ve sediment taşınmasında belirgin bir azalma beklenmektedir. Bitki kök sistemlerinin toprağı stabilize etmesi, malçlama uygulamalarının yüzey koruması sağlaması ve drenaj sistemlerinin etkin çalışması, erozyon kontrolünde başlıca etkenler oluşturacak yöntemlerdir.

Bu bulgu, literatürde bitkisel örtünün erozyon kontrolündeki etkinliğini gösteren çalışmalarla uyumludur. Özellikle şev stabilizasyonunda derin köklü türlerin (*Quercus* spp., *Pinus* spp.) ve yüzey örtücü türlerin birlikte kullanılmasının sinerjik etki yarattığı belirlenmiştir.

4. Sonuçlar

Bu çalışma, TÜMAD Madencilik işletme sahasında madencilik faaliyetleri sonucu bozulan ekosistem bileşenlerinin sistematik, bilimsel ve sürdürülebilir bir rehabilitasyon yaklaşımıyla yeniden yapılandırılmasını hedefleyen kapsamlı bir programın sonuçlarını ortaya koymaktadır. 48 aylık uygulama süresi boyunca gerçekleştirilmesi planlanan toprak iyileştirme, bitkilendirme, erozyon kontrolü ve ekosistem izleme stratejileri, alanın hem kısa vadede ekolojik işlevsellik kazanmasını hem de uzun vadede doğal bir bitki ve toprak rejimine kavuşmasını sağlamaktadır.

Proje kapsamında elde edilen başlıca sonuçlar şunlardır:

- Toprak iyileştirme:** Organik madde uygulamaları, pH düzenlemesi ve mikrobiyal aşılama sayesinde toprağın fiziksel, kimyasal ve biyolojik özelliklerinde belirgin iyileşme sağlanmış; organik madde oranı ve mikrobiyal aktivite artmış, pH hedef aralığa (6.0-7.5) getirilmiştir.
- Bitki örtüsü tesisi:** Yerel ve ekolojik uyumu yüksek türlerin kullanıldığı kademeli bitkilendirme yaklaşımıyla, alanda öncü tür tohumlamasıyla süreç başlatılmış ve takibi sağlanmaktadır.
- Bioçeşitlilik geri dönüşü:** Entomofauna izleme çalışmaları, özellikle tozlayıcı gruplar ve toprak faunasında belirgin bir artış olduğunu göstermiş; mikrohabitat yapılarının kurulması gerçekleştirilerek kolonizasyon hızlandırılacaktır.
- Erozyon kontrolü:** Bitki kök sistemlerinin toprağı stabilize etmesi ve malçlama uygulamaları sayesinde erozyon oranında azalma elde edilmesi öngörülmektedir.

Bu proje, madencilik sonrası arazi yönetimine yönelik ulusal ve uluslararası iyi uygulamalarla uyumlu, bilimsel temelli, izlenebilir ve tekrarlanabilir bir model ortaya koymaktadır. Özellikle ekosistem temelli rehabilitasyon yaklaşımının -fiziksel, kimyasal ve biyolojik yöntemlerin entegrasyonu ile - maden sahalarının ekolojik olarak işlevsel hale getirilmesinde ne denli etkili olduğu gösterilmiştir. TÜMAD sahasında yürütülen bu çalışmaların, benzer özelliklere sahip diğer maden alanlarına da yol gösterici olması beklenmektedir.

Bununla birlikte, literatürde vurgulandığı gibi, maden sahası restorasyon çalışmalarının başarısının değerlendirilmesinde kısa vadeli göstergelerin yanı sıra uzun vadeli süksesyon süreçlerinin, besin döngüsünün ve tür etkileşimlerinin izlenmesi de gereklidir. Bu nedenle, proje kapsamında oluşturulan izleme altyapısının ve CBS tabanlı veri yönetim sisteminin uzun yıllar boyunca sürdürülmesi, elde edilen kazanımların kalıcılığı açısından büyük önem taşımaktadır.

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Sürdürülebilir Madencilik Yaklaşımıyla Sosyal, Çevresel ve Ekolojik Rehabilitasyon Çalışmaları

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Özet

Madencilik faaliyetleri sonrasında bozulan alanların çevresel ve ekolojik açıdan yeniden kazanılması sürdürülebilir madencilik anlayışının temel bileşenlerinden biridir. Bu çalışmada Acacia Maden İşletmeleri tarafından yürütülen rehabilitasyon ve sosyal kalkınma projeleri değerlendirilmiştir. Çalışma kapsamında maden sahalarında toprak analizleri gerçekleştirilmiş ve elde edilen bulgular doğrultusunda uygun bitkilendirme yöntemleri belirlenmiştir. Çorakoğlu pasa döküm sahasında yaklaşık 1.500.000 m² alanda bitkisel toprak serimi, tohumlama ve fidan dikimi uygulamaları gerçekleştirilmiştir. İlk aşamada uygulanan hydromulching yöntemi yüksek maliyet nedeniyle sınırlı kalmış, bunun yerine yerel katılımlı alternatif tohumlama yöntemi geliştirilmiştir. Bu yöntem sayesinde geniş alanların daha düşük maliyetle rehabilite edilmesi mümkün olmuştur. Ayrıca mera iyileştirme, tarımsal sulama, seracılık, yenilenebilir enerji ve eğitim projeleriyle bölgesel sosyo-ekonomik gelişim desteklenmiştir. Elde edilen sonuçlar, eş zamanlı rehabilitasyon uygulamalarının ekosistem iyileşmesini hızlandırdığını ve yerel toplum katılımının sürdürülebilir madencilik uygulamalarında önemli rol oynadığını göstermektedir.

Anahtar Kelimeler: Sürdürülebilir madencilik, Maden sahası rehabilitasyonu, Eş zamanlı rehabilitasyon, Sosyo-ekonomik gelişim projeleri.

Abstract

Mining activities significantly alter natural ecosystems; therefore, post-mining rehabilitation has become a critical component of sustainable mining practices. This study evaluates the environmental rehabilitation and socio-economic development projects implemented by Acacia Mining Operations. Within the scope of the study, detailed soil analyses were conducted in the mining areas, and appropriate revegetation and rehabilitation strategies were determined based on the obtained results. Rehabilitation activities were carried out on approximately 1,500,000 m² of waste rock dump areas in the Çorakoğlu site through topsoil spreading, seeding, and tree planting applications. Although hydromulching was initially applied on a limited area, its high cost led to the development of an alternative community-based seeding method. This approach enabled the rehabilitation of large areas at lower cost while encouraging local participation. Additionally, biodiversity was enhanced through the planting of various tree species. Observations indicated improved vegetation cover, increased surface stability, and reduced erosion risk. The results demonstrate that simultaneous rehabilitation practices combined with community involvement contribute significantly to sustainable mining and ecosystem recovery.

Keywords: Sustainable mining, Mining site rehabilitation, Simultaneous rehabilitation, Socio-economic development projects.

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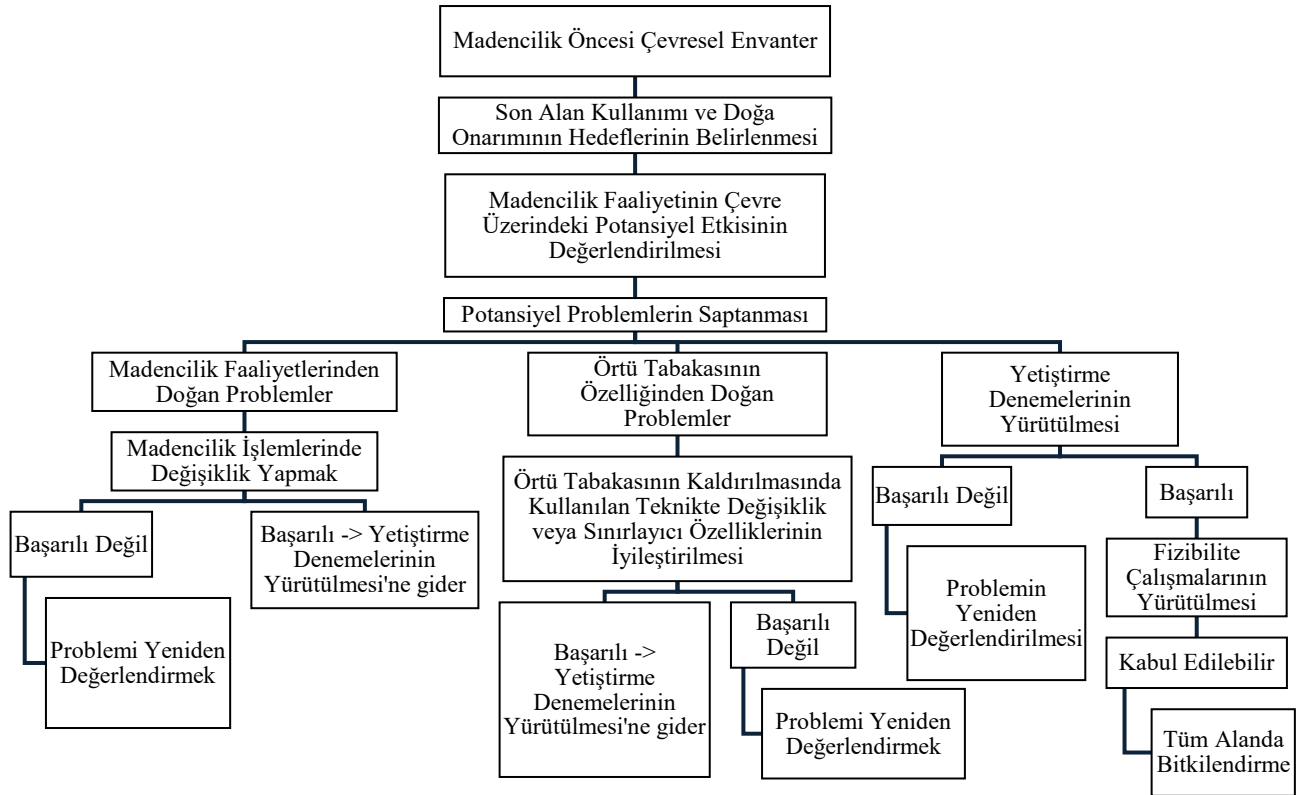
1.Giriş

Madencilik faaliyetleri alınması planlanan cevherin ekonomik ömrü ile sınırlı geçici faaliyetleri içermektedir. Bu geçici süreç tek bir bakış açısıyla değerlendirilmemelidir. Bu sürecin içerisinde ve süreç tamamlandığında sosyal, çevresel ve ekolojik olarak birçok çalışma yapılmaktadır. Yöreyle sosyo-ekonomik değer katılması bunun yanı sıra madencilik faaliyetleri nedeniyle bozulan, topoğrafyası değişen alanlara yönelik; emniyetli hâle getirme, düzenleme, duraylılığı sağlama, düzeltme, üst toprağı serme, tohum ekme, fidan dikme, arazi yapısı uygun yerlerde rekreasyon alanları oluşturma, bitkilendirme, ağaçlandırma, kimyasal ve fiziksel iyileştirme kapsamında yapılan çalışmaları da içinde barındırmaktadır (T.C. Resmi Gazete. 2026).

Maden sektörü stratejileri arasında kritik bir kavram haline gelen “Sürdürülebilir Madencilik”, sektöre yön veren temel yaklaşımı ifade etmektedir Sürdürülebilirlik, toplumun mevcut ihtiyaçlarını, gelecek nesillerin kendi ihtiyaçlarını karşılama yeteneğinden ödün vermeden dengelemekle ilgilidir (Strateji ve Bütçe Başkanlığı.2026). Sürdürülebilir madencilik ise maden kaynaklarının çıkarılması ve işlenmesi süreçlerinde ekonomik verimlilik, çevresel koruma ve sosyal sorumluluk ilkelerini birlikte gözetilen madencilik anlayışıdır. Bu yaklaşım Sürdürülebilir kalkınma amaçları ile de uyumludur. Sürdürülebilir madencilik, sadece maden çıkarmayı hedeflemez, doğaya, insana ve ekonomiye dengeli şekilde değer üretmeyi hedefleyen bütüncül bir yönetim felsefesidir.

Acacia Maden İşletmeleri olarak stratejilerimizi; yönetimde sorumlu, çevrede duyarlı ve insana saygılı bir yaklaşım temelinde şekillendirmektedir.

Tablo 1: Doğa onarımı, rehabilitasyon programının aşamaları (Michaud, 1981).



Sürdürülebilirliği iş stratejimizin merkezine konumlandırıyor, değer üretirken gelecek nesillere karşı sorumluluk bilinciyle hareket ediyoruz. Ekonomik başarıyı; çevresel duyarlılık, sosyal fayda ve güçlü kurumsal yönetim ilkeleriyle birlikte ele alıyoruz. Faaliyetlerimizi yürütürken doğal kaynakların verimli kullanımını, çevresel etkilerin azaltılmasını ve operasyonel süreçlerimizin sürekli iyileştirilmesini temel önceliklerimiz arasında görüyoruz. Riskleri erken aşamada tespit eden ve uzun vadeli etkileri gözetilen yönetim anlayışımızla, sürdürülebilir büyümeyi güvence altına alıyoruz.

Çevresel sorumluluğumuz olan faaliyetlerimizi sürdürülebilirlik ilkeleri doğrultusunda yürütüyoruz. Doğal kaynakların korunması, çevresel etkilerin azaltılması ve faaliyet sonrası alanların yeniden doğaya kazandırılması temel önceliklerimiz arasında yer alıyor.

Özellikle maden sahasında rehabilitasyon çalışmalarına büyük önem veriyoruz. Faaliyet süresi boyunca ve sonrasında yürüttüğümüz rehabilitasyon projeleri ile bozulan alanların yeniden doğal yapısına kavuşturulmasını, biyolojik çeşitliliğin desteklenmesini ve ekosistem dengesinin yeniden tesis edilmesini amaçlıyoruz. Toprak iyileştirme, ağaçlandırma ve peyzaj düzenlemeleriyle sahaların güvenli, verimli ve çevreyle uyumlu biçimde yeniden kazandırılmasını sağlıyoruz. Bununla yetinmeyip yerel kalkınmaya destekleyen bütüncül bir yaklaşım sunmaktayız.

Faaliyet gösterdiğimiz bölgelerde toplumla güçlü ve samimi bağlar kurmaya büyük önem veriyoruz. Eğitim, sağlık, tarım, hayvancılık ve çevresel sürdürülebilirlik alanlarında yürüttüğümüz çalışmalarla bulunduğumuz çevreye katkı sağlamayı; yalnızca ekonomik değil, aynı zamanda sosyal anlamda da değer üretmeyi hedefliyoruz.

Temelde potansiyel problemlerin saptanması, sonra problemleri madencilik faaliyetlerinden doğan ya da örtü tabakasının özelliğinden doğan problemler olmak üzere genelde iki kısımda ele alıyoruz. Probleme bağlı olarak madencilik işlemlerinde ya da örtü tabakasının kaldırılmasında kullanılan teknikte değişiklik yapılması veya sınırlayıcı özelliklerinin iyileştirilmesi şeklinde alınan yöntemlerde başarı durumuna göre aşağıda yer alan şemayı takip ediyoruz. (Ulusoy Y. 2012).

Bu doğrultuda hayata geçirdiğimiz projeler aşağıda sunulmaktadır:

1.1. Çorakoğlu Rehabilitasyon Projesi

Türkiye'nin en büyük açık ocak bakır maden işletmesinde bulunan iki farklı pasa döküm alanında doğal bitki örtüsünün geri kazandırılmasını amaçlayan kapsamlı bir rehabilitasyon çalışması yapılmaktadır. Yaklaşık 1,9 milyon m² büyüklüğündeki bu alanlarda, toprağın onarılması ve sürdürülebilir bir ekosistem oluşturulması hedeflenmiştir.

Başlangıçta, alanın yeşillendirilmesi için hydromulching tekniği (özel bir tohumlama ve besin taşıma tekniği) denenmiş, ancak maliyetlerin yüksek olması nedeniyle farklı yöntemlere geçiş yapılmıştır. Bölgedeki yerel halkın katılımıyla ve küçük tarım ekipmanı kullanılarak tohumlama yapılmıştır. Bu yaklaşım, yalnızca maliyeti azaltmakla kalmamış, aynı zamanda toplumun katılımını sağlamış ve bölgedeki doğal kaynakların kullanılmasını olanak tanımıştır. Tohum karışımlarında ise, taban besin dengesi göz önünde bulundurulmuş, doğal bitki örtüsünün hızlı ve sürdürülebilir bir şekilde geri kazanılması için çevresel sürdürülebilirlik ilkelerine uygun bir destek sağlanmıştır.

Projenin temel hedefi, alanların en hızlı ve doğal yollarla yeniden yeşillendirilmesi ve bu süreçte çevreye en az müdahale ile kalıcı bir bitki örtüsünün oluşturulmasının sağlanmasıdır.

Proje Hedefleri:Ekolojik Rehabilitasyon: Maden sahasında bozulan ekosistemi eş zamanlı olarak iyileştirerek doğal bitki örtüsünü geri kazandırmak.

Sürdürülebilir Rehabilitasyon: Yüksek maliyetli yöntemlerden kaçınarak maliyet-etkin ve sürdürülebilir bir çözüm sunmak.

Yöre Halkının Katılımı: Yöre halkının projeye katılımı hem sosyal sorumluluk açısından hem de yerel bilgi birikiminden faydalanmak açısından büyük bir avantaj sağlamıştır. Yerel topluluklara rehberlik ederek ve onların deneyimlerinden faydalanarak süreci daha etkili hale getirilmiştir.

Doğayı Yeniden Canlandırma: Toprak yapısını doğal bir şekilde geri kazandırarak, doğanın kendi kendini yenilemesi sağlanmıştır.

Proje alanımız olan Çorakoğlu pasa döküm sahası, 220 metre yüksekliğinde 22 adet basamağı ve 35°'lik genel şev açısı ile toplam 155 hektarlık yüzölçümüne sahip olan büyük bir rehabilitasyon sahasıdır. Bu tür çok basamaklı ve geniş alanlarda yapılacak ekolojik rehabilitasyon çalışmaları, bitki örtüsünün basamaklar boyunca eşit şekilde dağılımı ve alanın stabilizasyonunu sağlamak açısından zorluklar içermektedir. Projenin ilk aşamasında bütün şev yüzeyleri maden başlangıcında depolanan

nebatı (bitkisel toprak) ile örtülmüştür. Bu aşama da yaklaşık 1,000,000 USD 'lık harcama yapılmıştır. İkinci aşamada ise yüzeylerin tutuculuğunun sağlanması ve doğanın yeniden kazanımı için çalışmalarına start verilmiştir. Bu çalışmaya ilk olarak 114,000 m² alanda hydromulching uygulaması denemeleri ile başlanmıştır. Bu uygulama için yaklaşık 350,000 USD'lık harcama yapılmıştır. 1,500,000 m²'lik alan için bu uygulama maliyetinin çok fazla olacağı düşünülmüş ve alternatif yollara gidilmiştir. Üçüncü aşamada ise basamaklardaki ihtiyaçlarına göre özel tohum karışımları ve rehabilitasyon teknikleri uygulanması ile sahanın tamamına 40 ton, tohum ve gübre (toprağı güçlendirmek için taban gübresi, korunga ve fiğ tohumu) karışımı atılmıştır. Bu uygulama küçük bir tarım ekipmanı ile yöre halkından kadınların yardımı alınarak yapılmıştır. 1,386,000 m² alan için yaklaşık 119,000 USD'lık harcama ile tamamlanmıştır.



Şekil 1: Bitkisel toprak serimi-Hydromulching-Tohum karma işi

Rehabilitasyon sahasında Hanönü Orman İşletme Müdürlüğü ile toplam **236.236** adet (2.754 Ceviz (*Juglans regia*), 206.108 Akasya (*Robinia pseudoacacia* L.), 20.237 Karaçam (*Pinus nigra*), 150 Sarıçam (*Pinus silvestris*), 5.254 Sedir (*Cedrus*), 130 İğde (*Elaeagnus angustifolia*), 500 Badem (*Prunus dulcis*), 400 Elma (*Malus domestica*), 50 Kuşburnu (*Rosa canina*), 53 Ladin (*Picea*), 500 Ihlamur (*Tilia*), 100 Ahlat (*Pyrus*) fidan dikim işlemi yapılmıştır.



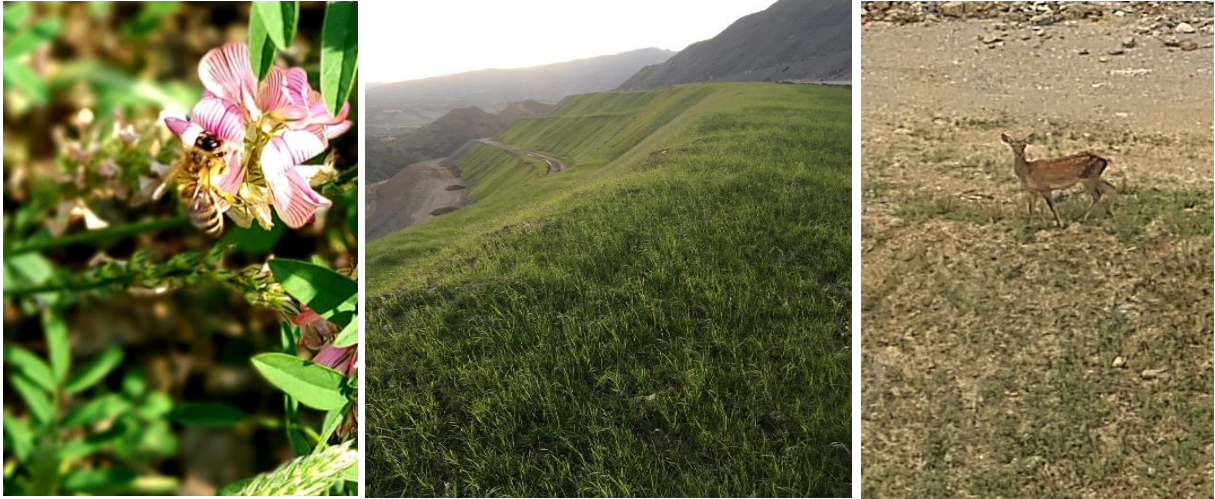
Şekil 2: Fidan dikim işleri

Rehabilitasyon sahasında biyoçeşitliliğin artırılması ve ekosistemin yeniden canlandırılması için adımlar atılmıştır. Farklı türdeki fidanların dikimi, alandaki flora çeşitliliğini zenginleştirirken aynı zamanda toprak stabilitesi ve erozyon kontrolü gibi ekolojik faydalar da sağlayacaktır. Doğal bir ekosistem oluşumunu destekleyerek bölgenin çevresel sürdürülebilirliğine önemli katkılarda bulunacaktır.



Şekil 3: 2021 Pasa döküm sahası- 2023 Sonrası Rehabilitasyon Sahası

Bu proje, maliyetlerin etkin yönetimini ve çevresel sürdürülebilirliği aynı anda sağlamayı hedefleyen yenilikçi bir yaklaşıma sahiptir. Yerel kaynakların ve yöre halkının katılımı sayesinde, hem sosyo-ekonomik hem de çevresel olarak daha sürdürülebilir sonuçlar elde edilmektedir. Doğru tohum seçimi ve yerel katılım sayesinde, büyük alanların düşük maliyetle rehabilite edilmesi amaçlanmış, böylece uzun vadeli çevresel iyileştirme hedefleri desteklenmiştir. Aynı zamanda, yeni başlamış olduğunuz pasa döküm sahasında maliyetlerin optimize edilmesi ve pasa sahasının doğaya en kısa sürede yeniden kazandırılması için eş zamanlı rehabilitasyon adımları atılmaktadır. Bu yaklaşım, doğanın kendi döngüsüne uyumlu bir şekilde hareket ederek saha kapatılmadan önce çevresel iyileştirme çalışmalarının tamamlanmasına olanak tanıyacaktır.



Şekil 4: Eş zamanlı rehabilitasyon çalışması

Arıların, geyiklerin, kekliklerin ve gelinciklerin doğal yaşam alanlarına geri dönmesi mümkün kılınmıştır. Tohumlama sürecine toplumun dahil edilmesi hem ekosistemin yeniden canlanmasını destekledi hem de çevresel sürdürülebilirlik için yerel bir sahiplenme yaratmış oldu.



Şekil 5: Eş zamanlı rehabilitasyon çalışması

Diğer pasa sahasında ise döküm çalışmalarının tamamlandığı kotlarda eş zamanlı olarak yapılan rehabilitasyon çalışmaları, alanın bitkisel toprak ve uygun tohumlarla buluşturulması sayesinde doğanın kendi kendini yenileyebilmesi için gerekli koşulları sağlıyor. Böylece, döküm süreci boyunca alanın yeniden yeşermesi ve doğal yaşamın geri dönmesi teşvik edilmiş oluyor. Bu yaklaşım, doğal kaynakları korurken madencilik faaliyetlerinin çevresel etkisini minimize ederek gelecekte daha sürdürülebilir ve yaşanabilir bir çevre sağlama hedefine katkıda bulunmaktadır.

1.2. Mera İyileştirme Projeleri

Acacia Maden İşletmeleri tarafından proje sahalarına yakın yerleşim yerlerinde gerçekleştirilen sosyo-ekonomik ve demografik anket çalışmaları sonucunda, bölge halkının temel geçim kaynaklarının tarım ve hayvancılık olduğu tespit edilmiştir. Açık ocak, cevher zenginleştirme tesisi, atık depolama tesisi ve pasa döküm sahaları gibi proje alanlarının yerleşim yerlerine yakın konumda bulunması nedeniyle, faaliyetlerimizden kaynaklanabilecek mera alanlarının daralması gibi olası etkilerin en aza indirilmesi amacıyla “Mera İyileştirme Projeleri” hayata geçirilmiştir.

Bu kapsamda Dereköy bölgesinde 2020 yılında yaklaşık 40 dönümlük bir alanda projenin ilk etabı uygulanmıştır. Ancak 2022 yılında yaşanan sel felaketi sonucunda proje alanı zarar görmüş, bunun üzerine gerekli iyileştirme ve rehabilitasyon çalışmaları gerçekleştirilmiştir. Yapılan çalışmaların ardından 2025 yılında proje yeniden başlatılarak yaklaşık 45 dönümlük alanda çok yıllık sertifikalı mera tohumu ekimi gerçekleştirilmiştir.

Proje kapsamında mera alanının sürdürülebilir şekilde kullanılabilmesi ve sulama ihtiyacının karşılanabilmesi amacıyla 250 metre beton sulama kanalı ve 550 metre uzunluğunda basınçlı sulama sistemi temin edilmiştir. Söz konusu altyapı ekipmanları ilgili Muhtarlığa teslim edilerek hayvan yetiştiricilerinin kullanımına sunulmuştur.



Şekil 6: 2025 Dereköy Mera İyileştirme Projesi

Etki alanımızda bulunan diğer bir yerleşim yeri olan Karayaprak Mahallesi bölgesinde 2023 yılında Kastamonu İl Tarım Müdürlüğü ile imzalanan protokol kapsamında 52,7 dönümlük mera arazisinde iyileştirme çalışmaları tamamlanmış ve hayvan sahiplerinin kullanımı için Muhtarlığa teslim edilmiştir.



Şekil 7: 2024 Karayaprak Mera İyileştirme Projesi

1.3. Tarımsal Sulama Suyu Projeleri

Etki alanı içerisinde yer alan yerleşim yerlerinde tarımsal faaliyetlerde bulunan hanelerin desteklenmesi ve tarımsal üretimin sürdürülebilirliğinin sağlanması amacıyla tarımsal sulama suyu projeleri hayata geçirilmiştir. Bu projeler kapsamında daha önce yalnızca kısmen sulanabilen toplam 1.095 parselde yer alan 3.507 dekar tarım arazisi, gerçekleştirilen altyapı çalışmaları sayesinde tamamen sulanabilir hale getirilmiştir. Söz konusu sulama projelerine entegre olarak, bölgede tarımla uğraşan hanelerin bilgi ve becerilerinin geliştirilmesi amacıyla tarımsal eğitim programları düzenlenmektedir. Bu eğitimler aracılığıyla üreticilerin modern tarım uygulamaları, verimli su kullanımı ve sürdürülebilir üretim yöntemleri konusunda bilinçlendirilmesi hedeflenmiş ve bilinçli ve verimli üretim süreçlerinin desteklenmesi amaçlanmıştır.

- Yılanlı – Karayaprak: 630 m beton kanal - 450 m boru hattı - 450 dekar sulanabilir arazi
- Dereköy: 224 m beton kanal - 2250 m boru hattı - 350 dekar sulanabilir arazi
- Bağdere: 2400 m beton sulama kanalı - 862 dekar sulanabilir arazi
- Küreçay: 3500 m beton kanal - 1845 dekar sulanabilir arazi



Şekil 8: 2019-2023 Tarımsal Sulama Suyu Projeleri

1.4. Modern Seracılık Projesi

Hayata geçirilen Tarımsal Sulama Suyu Projeleri ile entegreli olarak tarımsal üretime destek vermek, iklimsel değişiklikler nedeniyle ürünlerin etkilenmesini önlemek, iş gücünü en aza indirmek ve damla sulama sistemlerinin kullanımını yaygınlaştırarak kontrolsüz sulamanın önüne geçilmesi amacıyla modern seracılık projeleri hayata geçirilmektedir. Etki alanında bulunan yerleşim yerlerinde şu ana kadar 6 adet sera projesi hayata geçirilmiştir. İlerleyen süreçte projelerin geliştirilerek devam ettirilmesi planlanmaktadır.



Şekil 9: 2022-2024 Seracılık Proje Örnekleri

1.5. Güneş Enerjisi Santrali Projesi

Sürdürülebilir ve çevreye duyarlı enerji üretimi vizyonumuz doğrultusunda, Ankara ili Polatlı ilçesi'nde 65.002 kWp kapasiteli Acacia Güneş Enerji Santrali (GES)'ni hayata geçirdik.



Şekil 10: Ankara Polatlı Acacia Güneş Enerji Santrali Projesi

Hanönü Belediyesi ile imzalanan iş birliği protokolü kapsamında 230 kWe kapasiteli bir Güneş Enerjisi Santrali (GES) projesi hayata geçirilmiştir. Gerçekleştirilen bu proje sayesinde belediyeye bağlı mahallelerde bulunan ortak kullanım alanlarının elektrik giderlerinin karşılanmasına katkı sağlanmaktadır.

Proje ile yenilenebilir enerji kaynaklarının kullanımının teşvik edilmesi, enerji maliyetlerinin azaltılması ve yerel yönetimlerin sürdürülebilir enerji uygulamalarına destek verilmesi amaçlanmaktadır.



Şekil 11: Hanönü Belediyesi Güneş Enerji Santrali Projesi

1.6. Sağlık Destek Projeleri

Kastamonu İl Sağlık Müdürlüğü ile imzalanan Sosyal Projeler İş birliği Protokolü kapsamında, ilçe merkezinde bulunan hastanenin fiziki teknik altyapısının yeterli olmaması sebebiyle ihtiyaç olan

alanlarda gerekli iyileştirme çalışmaları yapılmıştır. Buna bağlı olarak; 2024 yılında Hanönü Devlet Hastanesi Yataklı Servisleri, Diş Kliniği servisi için gerekli teknolojik malzeme ve ekipman desteği sağlanmıştır.2025 yılında ise Hanönü Toplum Sağlığı Merkezi'nde çalışan personellerin çalışma koşullarını iyileştirmek ve yöre halkının daha iyi koşullarda hizmet almasını sağlamak amacıyla teknolojik ekipman ve malzeme desteği sağlanmıştır.



Şekil 12: Hanönü Devlet Hastanesi ve Toplum Sağlığı Merkezi Sağlıkta Destek Proje Örnekleri

1.7. Eğitim Destek Projeleri

1.7.1. Hanönü Çok Programlı Anadolu Lisesi Maden Teknolojileri Bölümü

Hanönü İlçesi'nde bulunan Çok Programlı Anadolu Lisesi'nde Maden Teknolojileri Bölümü'nün açılmasına Milli Eğitim Bakanlığı nezdinde öncülük edilmiştir. 2017 yılında Acacia'nın girişimleri ile Hanönü İlçe Milli Eğitim Müdürlüğü ile "Maden Teknolojileri Bölümü" açılması için protokol imzalanmıştır.

2018 – 2019 eğitim ve öğretim yılı başında 12 öğrencinin kaydolması ile bu bölüm faaliyete geçmiş ve ilk mezunlarını 2022 yılında vermiştir. 2022-2023 yılı eğitim döneminde Maden Teknolojileri Bölümü' nü 10 öğrenci, 2024-2025 eğitim-öğretim yılında ise 14 öğrenci Maden Teknolojileri Bölümü' nü tercih etmiştir.

Bu bölümde öğrenim gören bütün öğrencilerin staj programları, mezun olan ve üniversite kazanan öğrencilerin burs destekleri ve uygun olan pozisyonlarda istihdam edilmeleri Acacia Maden İşletmeleri tarafından sağlanmıştır.

1.7.2. Burs Programı

Acacia Maden İşletmeleri olarak 2021 yılında başlatılan "Burs Programı" kapsamında üniversite ve teknik lise öğrencilerine burs imkânı sunulmuştur. Bu program kapsamında hazırlanan "Burs Prosedürü" kriterlerine göre burs almaya hak kazanan öğrencilerin belirlenen başarı şartlarını sağladıkları sürece eğitim öğretim süresi boyunca bursları hesaplarına ödenmektedir.

2021 yılında toplam 16 üniversite öğrencisine, 2022 yılında toplam 16 üniversite öğrencisine, 2023 yılında toplam 44 üniversite öğrencisine ve 3 teknik lise öğrencisine, 2024 yılında toplam 51 üniversite öğrencisi, 3 teknik lise öğrencisine, 2025-2026 yıllarında ise toplam 65 üniversite öğrencisi ve 4 teknik lise öğrencisine burs verilmektedir.



Şekil 13: Maden Teknolojileri Bölümü

1.7.3. Hanönü Anaokulu Fiziksel ve Teknik Altyapı Geliştirme Projesi

Geleceğimizin teminatı çocuklarımız için daha güvenli, daha donanımlı ve daha modern bir eğitim ortamı oluşturmak amacıyla Hanönü Anaokulunda Fiziksel ve Teknik Altyapı Geliştirme Projesi kapsamında altyapı çalışmaları, sınıflar, yemekhane, ortak oyun alanları, oyun grupları ve teknik bütün donanımlar baştan sona yenilendi ve eğitim ortamı daha modern bir hale getirilerek çocuklarımızın hayal gücünü geliştirecek ve eğitime ilk adımlarını atacakları sıcak bir yuva haline getirildi.



Şekil 14: Hanönü Anaokulu Fiziksel ve Teknik Altyapı Geliştirme Projesi

Yerel Satınalma

Hanönü Taşıyıcılar Kooperatifi 2014 yılında ilçede taşımacılık yapan kişilerin bir araya gelmesi ile kurulmuş ancak aktif olarak faaliyet göstermemektedir.

2019 yılında firmamızın konsantrite üretimine başlayacak olması sebebiyle kooperatif yönetimi ile gerekli görüşmeler yapılarak konsantrite nakliyesinin yapılması için sözleşmeler imzalanmış ve kooperatif aktif hale getirilmiştir. Bu çalışma ilçe merkezli olarak yapılmış en büyük yerel satınalma desteklerinden birisidir.



Şekil 15: 2019-2025 Hanönü Taşıyıcılar Kooperatifi

Acacia Maden İşletmeleri'nin bölgede faaliyet göstermeye başladığı ilk yıllarda yapmış olduğu girişimler sonucu kurulan "Hanönü Kadın Girişimciler Derneği" yine firmamızın destekleri ve

girişimleri birlikte 2023 yılında “Hanönü Kadın Girişimciler Kooperatifi” adı altında kooperatifleşmiş ve aktif olarak ticari gelir sağlamaktadır. 2026 yılında Kastamonu İl Tarım Müdürlüğü ile imzalanan protokole istinaden üretim amaçlı projeler ile desteklenmeye devam etmektedir.

Bunun yanı sıra ilçe merkezinde faaliyet gösteren restoran sahipleri ile görüşülmüş ve iki firmanın ortaklığı ile bir catering şirketi kurulmuş Acacia Maden İşletmeleri’ne yemek hizmeti vermeye devam etmektedirler.



Şekil 16: 2017-2025 Hanönü Kadın Girişimciler Kooperatifi

2. Materyal ve Metot

Projeler kapsamında çalışma sahalarında ayrıntılı toprak analizleri gerçekleştirilmiştir. Toprak örnekleri, belirlenen noktalardan uygun derinliklerde alınarak laboratuvar ortamında analiz edilmiştir. Analizlerde toprağın fiziksel ve kimyasal özellikleri (pH, organik madde miktarı, makro ve mikro besin elementleri vb.) değerlendirilmiştir. Örnekleme, analiz ve sonuçların yorumlanması süreçlerinde ziraat mühendisi desteği alınmıştır. Ayrıca, yörenin ihtiyaçları bölge halkı ile değerlendirilmiş; yerel paydaşlarla yapılan anketler ve görüşmeler sonucunda proje kararları şekillendirilmiştir.

3. Bulgular ve Tartışma

Bu çalışmada elde edilen bulgular, büyük ölçekli maden sahalarında gerçekleştirilen rehabilitasyon uygulamalarının çevresel iyileşme açısından önemli sonuçlar ortaya koyduğunu göstermektedir. Özellikle bitkisel toprak serimi ve uygun tohum karışımlarının kullanılması, yüzey stabilitesinin sağlanması ve erozyon riskinin azaltılması açısından etkili bir yöntem olarak öne çıkmaktadır. Hydromulching tekniği literatürde geniş alanların hızlı şekilde bitkilendirilmesinde başarılı bir yöntem olarak kabul edilmekle birlikte, çalışmada elde edilen sonuçlar maliyet açısından bu yöntemin her saha için uygulanabilir olmadığını göstermiştir.

Alternatif olarak geliştirilen yerel katılımlı tohumlama yöntemi hem ekonomik açıdan daha sürdürülebilir bir çözüm sunmuş hem de yerel toplulukların projeye katılımını artırmıştır. Bu durum, sürdürülebilir madencilik uygulamalarında sosyal boyutun çevresel rehabilitasyon kadar önemli olduğunu ortaya koymaktadır. Ayrıca farklı türlerde gerçekleştirilen fidan dikimleri sayesinde sahada biyolojik çeşitlilik desteklenmiş ve doğal ekosistem süreçlerinin yeniden oluşmaya başladığı gözlemlenmiştir.

Fauna türlerinin yeniden sahada gözlemlenmesi, ekosistemin fonksiyonel olarak yeniden işlemeye başladığını göstermektedir. Bununla birlikte eş zamanlı rehabilitasyon yaklaşımı, maden faaliyetleri devam ederken çevresel iyileştirme çalışmalarının yürütülmesine olanak tanıyarak saha kapatma sürecinin daha etkin şekilde yönetilmesine katkı sağlamaktadır. Bu yaklaşım, madencilik faaliyetlerinin çevresel etkilerinin azaltılmasında önemli bir uygulama modeli sunmaktadır.

4. Sonuçlar

Bu çalışma kapsamında gerçekleştirilen rehabilitasyon ve sosyal kalkınma projeleri, sürdürülebilir madencilik uygulamalarının çevresel ve toplumsal boyutlarını ortaya koymaktadır. Çorakoğlu pasa döküm sahasında uygulanan bitkisel toprak serimi, tohumlama ve fidan dikimi çalışmaları sayesinde bozulan alanların yeniden ekosisteme kazandırılması yönünde önemli ilerlemeler sağlanmıştır.

Hydromulching yöntemi teknik olarak başarılı sonuçlar vermesine rağmen yüksek maliyet nedeniyle geniş alanlarda uygulanabilir bulunmamıştır. Bunun yerine geliştirilen yerel katımlı tohumlama yöntemi maliyet etkinliği ve uygulama kolaylığı açısından daha sürdürülebilir bir alternatif olarak öne çıkmıştır. Ayrıca eş zamanlı rehabilitasyon uygulamalarının, madencilik faaliyetleri devam ederken çevresel iyileşmenin başlamasını sağlayarak rehabilitasyon sürecini hızlandırdığı görülmüştür.

Yerel halkın projelere aktif katılımı sosyal sürdürülebilirliği desteklemiş ve rehabilitasyon çalışmalarının yerel ölçekte benimsenmesine katkı sağlamıştır. Bunun yanı sıra mera iyileştirme, tarımsal sulama, seracılık ve eğitim projeleri gibi sosyal yatırımlar bölgesel kalkınmaya destek olmuştur. Sonuç olarak çevresel rehabilitasyon uygulamalarının sosyal projelerle birlikte planlanması sürdürülebilir madencilik yaklaşımının uygulanabilirliğini güçlendirmekte ve madencilik sonrası alanların doğaya yeniden kazandırılması sürecinde etkili bir model sunmaktadır.

Teşekkür

Bu çalışmanın gerçekleştirilmesinde sağladıkları destek ve katkılarından dolayı Acacia Maden İşletmeleri yönetimine teşekkür ederiz. Projelerin yürütülmesi sürecinde değerli katkı ve destekleri için İşletme Müdürü Mehmet Avcı'ya ve Maden Müdürü Gökhan Çelik'e ayrıca teşekkürlerimizi sunarız. Çalışma sürecinde saha organizasyonu ve iletişim konusunda destek sağlayan Halkla İlişkiler biriminde görev yapan çalışma arkadaşlarımıza katkılarından dolayı teşekkür ederiz. Ayrıca rehabilitasyon ve sosyal projelerin uygulanması aşamalarında gösterdikleri iş birliği, katılım ve destekleri için bölge halkına teşekkürlerimizi sunarız. Yerel topluluğun katkıları, sürdürülebilir madencilik uygulamalarının başarıyla hayata geçirilmesinde önemli bir rol oynamıştır.

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Öksüt Madencilik A.Ş. Develi Şubesi Rehabilitasyon Çalışmaları

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Özet

Madencilik projelerinde kapatma ve rehabilitasyon planlaması, işletme sürecinin ayrılmaz bir bileşeni olarak değerlendirilmekte; çevresel etkilerin yönetimi, uzun vadeli fiziksel bütünlüğün korunması ve jeokimyasal davranışın kontrolü açısından stratejik bir rol üstlenmektedir. Açık ocak ve yığın liçi yöntemlerinin uygulandığı sahalarda özellikle atık kayaç depolama alanları ile liç yığınlarının kapatma tasarımı, hidrojeolojik koşullar, jeokimyasal koşullar, malzeme özellikleri ve jeoteknik parametrelerin birlikte ele alınmasını gerektirmektedir.

Kayseri ili Develi ilçesinde faaliyetlerini sürdüren Öksüt Madencilik'te, işletme döneminde yürütülen çevresel izleme faaliyetleri, numunelendirme programları ve mühendislik analizleri kapatma planlamasına eş zamanlı veri sağlamaktadır. Ekonomik Olmayan Kayaç Depolama (EOK) ve Yığın Liçi alanlarında gerçekleştirilen karakterizasyon çalışmaları, örtü tabakası tasarımlar, kolon testleri ve kavramsal modelleme uygulamaları, sahaya özgü uzun dönem performansın öngörülmesine yönelik teknik bir çerçeve oluşturmaktadır.

Bu bildiri, söz konusu çalışmaların kapatma planına entegrasyon sürecini disiplinler arası bir yaklaşım doğrultusunda ortaya koymayı hedeflemektedir.

Anahtar Kelimeler; Çevre, Maden, Madencilik sonrası, Rehabilitasyon

Özet

In mining projects, closure and rehabilitation planning is considered an integral part of the operational process; it plays a strategic role in managing environmental impacts, ensuring long-term physical integrity, and controlling geochemical behavior. In areas where open pit and heap leaching methods are applied, the closure design of waste rock storage areas and leach piles in particular requires the joint consideration of hydrogeological conditions, geochemical conditions, material properties, and geotechnical parameters.

At Öksüt Madencilik, which operates in the Develi district of Kayseri province, environmental monitoring activities, sampling programs, and engineering analyses carried out during the operating period provide data in parallel with closure planning. Characterization studies, cover layer designs, column tests, and conceptual modeling applications carried out in the Non-Economic Rock Storage (EOK) and Heap Leach areas establish a technical framework for predicting site-specific long-term performance.

This paper aims to present the integration process of these studies into the closure plan through an interdisciplinary approach.

Keywords; Environment, Mining, Post-mining, Rehabilitation

1. Giriş

Kayseri ili Develi ilçesinde açık ocak ve yığın liçi yöntemleri ile üretim faaliyetlerini sürdüren Öksüt Madencilik olarak, işletme sürecinde ortaya çıkabilecek çevresel etkilerin yönetimi amacıyla düzenli izleme programları, analiz çalışmaları ve kontrol mekanizmaları uygulamaktayız. Su kaynaklarının yönetimi, atıkların sınıflandırılması ve bertaraf süreçleri, sistematik bir çevresel yönetim çerçevesi içinde yürütmekteyiz. Ulusal mevzuat hükümleri ve uluslararası standartlar doğrultusunda sürdürülen bu uygulamalar, kapatma planlamasının bilimsel ve teknik temelini oluşturmaktayız.

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Bu doğrultuda, maden kapatma sürecine hazırlık kapsamında Ekonomik Olmayan Kayaç Depolama (EOK) ve Yığın Liçi alanlarında detaylı karakterizasyon çalışmaları gerçekleştirilmekte; örtü tabakası tasarımları mühendislik analizleri ile değerlendirilmektedir. Laboratuvar ölçekli kolon testleri ve kavramsal hidrojeolojik-jeokimyasal modelleme çalışmaları ile sahaya özgü uzun dönem davranışın öngörülmesi amaçlanmaktadır. İşletme aşamasında elde edilen izleme ve test verileri, rehabilitasyon stratejilerinin belirlenmesinde temel veri seti olarak kullanılmaktadır.

1.1. İşletme Sürecinde Çevresel Yönetim ve Kapatma Planlamasına Girdi Sağlayan Çalışmalar

İşletme aşamasında çevresel etkilerin etkin biçimde yönetilebilmesi amacıyla entegre bir çevre yönetim sistemi uygulanmaktadır. Bu sistem çerçevesinde, atık oluşumunun mümkün olduğunca kaynağında azaltılması, geri kazanım uygulamalarının yaygınlaştırılması ve atıkların özelliklerine göre sınıflandırılarak kontrol altına alınması temel prensip olarak benimsenmiştir. Tehlikeli nitelikteki atıklar, yürürlükteki mevzuat hükümlerine uygun şekilde tasarlanmış geçici depolama alanlarında muhafaza edilmekte ve lisanslı bertaraf veya geri kazanım tesislerine sevk edilmektedir.

Su yönetimi uygulamaları kapsamında proses suyu dengesinin takibi, yüzeysel akışın kontrolü ve yeraltı suyu seviyelerinin ve kalitesini izlenmesine yönelik çalışmalar düzenli olarak sürdürülmektedir. Bu amaçla oluşturulan izleme noktalarında belirli periyotlarla ölçüm ve numune alma işlemleri gerçekleştirilmekte, elde edilen veriler mansap ve memba ilişkisi gözetilerek teknik değerlendirmeye tabi tutulmaktadır. Maden sahası Develi Dağları olarak adlandırılan topoğrafyada konumlanması sebebi ile bölgede iklim kurak ve sıcak yazların ardından soğuk kışlar olarak karakterizedir. Maden sahası bulunduğu tepeler ve hidrolik ayrımlar sebebi ile su kalitesi izlemesi tesis üniteleri bazında ayrılmaktadır. Su kalitesi izleme programı mansap-memba ilişkisi gözetilerek oluşturulmuştur. Pasa sahası, açık ocaklar ve tesis üniteleri kendi özelinde yeraltısu ve yüzeysuyu akımı göstermektedir.

Sahanın etki çapında bulunan çevre yerleşkelerde yüzeysuyu ve yeraltısu kalitesi izlemesi gerçekleştirilmektedir. Maden sahasından çevresine akış gösteren kuru dere yatakları bulunmaktadır. Yağışlı sezonda mevsimsel olarak akış gösteren bu noktalarda yüzeysuyu kalitesi izlemesi gerçekleştirilmektedir, Bu alanlarda herhangi bir kirletici taşınımı tespit edilmemiştir; izleme sonuçları yasal limitler dahilindedir. Toplanan tüm izleme ve analiz sonuçları ilgili yasal düzenlemeler doğrultusunda raporlanmakta ve kapatma planlamasında kullanılmak üzere sistematik bir veri altyapısında kayıt altına alınmaktadır. Böylece işletme döneminde üretilen saha verileri, uzun dönemli çevresel performansın öngörülmesine ve rehabilitasyon tasarım kriterlerine katkı sağlamaktadır. İnşaat, üretim ve kapama dönemleri olarak programlanan izleme faaliyetleri verilerinin doğrulanması ve arşivlenmesi veri kalitesi, kullanılabilirliği açısından önem arz etmektedir. Bu kapsamda verilerin arşivlenmesi konusunda Mp5, Wire, PoweBi vb. veri tabanları kullanılmaktadır.

1.1.1. Ekonomik Olmayan Kayaç Depolama (EOK) Alanına Yönelik Teknik Çalışmalar

Ekonomik Olmayan Kayaç Depolama (EOK) alanında, sahayı temsil edecek dağılımı sağlayacak biçimde numune alma çalışmaları yürütülmekte ve analiz sonuçlarına bağlı olarak jeokimyasal karakterizasyon ve sınıflandırma yapılmaktadır. Yönetmeliklerde belirtilen tasarım kriterlerini kapsamında en verimli hale getirilmesi için elde edilen bu veriler temel girdi sağlayacaktır. Örtü tabakası tasarımı ise mevcut topoğrafik koşullar, malzemenin fiziksel ve kimyasal özellikleri ile uzun vadeli performans hedefleri birlikte değerlendirilerek geliştirilmektedir. Bakanlığımız tarafından belirlenen örtü tabakaları ve uluslararası en iyi uygulamalar gözetilerek test ve değerlendirme çalışmalarının yürütülmesi amaçlanmaktadır.

Kapatma tasarımının saha ölçeğinde doğrulanabilmesi amacıyla pilot uygulama niteliğinde örtü sistemleri inşa edilmeye başlanmıştır. Bu kapsamda farklı örtü konfigürasyonları sahada uygulanmakta ve söz konusu sistemlerin infiltrasyon kontrolü, yüzey akışının yönlendirilmesi ve fiziksel bütünlük performansı izleme programı kapsamında değerlendirilmektedir.

Pilot alanlarda kullanılan çeşitli malzeme kombinasyonları ile tabaka kalınlıkları, saha izleme sonuçları doğrultusunda karşılaştırmalı olarak analiz edilecektir. Bu süreçte su geçirgenliği, yüzey akış karakteristiği ve erozyona karşı dayanım gibi performans göstergeleri dikkate alınmaktadır.

Bu yöntem sayesinde tasarım süreci yalnızca teorik kabullere dayanmamakta; saha gözlemleri ile doğrulanan, performans temelli bir kapatma yaklaşımı geliştirilmektedir.

1.2.2. Yığın Liçi Alanında Karakterizasyon ve Kolon Testleri

Yığın liçi sahasında kapatma sonrasında oluşabilecek potansiyel sızıntı sularının jeokimyasal davranışın değerlendirilmesi amacıyla temsil kabiliyeti yüksek numune alma programı uygulanmakta ve laboratuvar ölçeğinde kolon deneyleri gerçekleştirilmektedir. Bu deneylerde farklı tasarım ve senaryo koşulları altında oluşan drenaj suyunun kimyasal karakteri, potansiyel metal mobilizasyonu ve zamana bağlı değişim eğilimleri analiz edilerek, yasal regülasyon limitleri altında kalacak şekilde kontrol mekanizmalarının tasarımı ve atıksu giderimi için kurulacak sistemin tasarım kriterlerinin belirlenmesi amaçlanmaktadır.

Kolon çalışmalarından elde edilen bulgular, örtü sistemlerinin teknik açıdan karşılaştırılmasına imkân tanımakta ve uzun dönemli çevresel performansın öngörülmesine yönelik mühendislik kararlarını desteklemektedir. Böylece kapatma tasarımında kullanılacak yaklaşım, deneysel veriler ışığında sahaya özgü olarak şekillendirilmektedir.

Bu çalışmalara ek olarak yığın liçi alanında sonik sondaj yöntemi ile numuneler alınacak olup bu numunelere vasıtası ile yığın liçinin farklı alanlarındaki cevherin nasıl fiziksel ve kimyasal özellik gösterdiği net bir şekilde belirlenecektir.

1.2.3. Hidrojeolojik ve Jeokimyasal Modelleme

Saha ölçeğinde yürütülen çalışmalar, hidrojeolojik ve jeokimyasal temelli sayısal modelleme yaklaşımları ile bütünleştirilmektedir. Yeraltı ve yüzey suyu sistemleri arasındaki etkileşim, depolama alanlarındaki malzeme özellikleri ve mevcut saha geometrisi birlikte ele alınarak olası kapatma senaryoları değerlendirmeye tabi tutulmaktadır.

Geliştirilen sayısal modeller aracılığıyla farklı tasarım alternatiflerinin uzun dönemli davranışı analiz edilmekte; su akış rejimi, potansiyel kirletici taşınımı ve sistem stabilitesi gibi parametreler bütüncül bir çerçevede incelenmektedir. Bu yaklaşım, kapatma planlamasında karar verme sürecinin ve kapatma sonrası izleme çalışmalarının bilimsel temele dayandırılmasına katkı sağlamaktadır.

1.2.4. Ekolojik Rehabilitasyon ve Biyoçeşitlilik Çalışmaları

Kapatma planlamasının ekolojik bileşeni kapsamında sahaya özgü bitkilendirme stratejileri geliştirilmektedir. Bu çerçevede oluşturulan Botanik Bahçe ve bitkisel koruma alanları aracılığıyla bölgeye ait endemik bitki türlerinin çoğaltılması ve sahadaki yetişebilecek bitki türlerinin kontrollü ortam koşullarında yetiştirilmesine yönelik çalışmalar sürdürülmektedir.

Bu uygulamalar, yerel ekosistem dinamiklerinin korunmasını desteklerken kapatma sonrası arazi kullanımına uygun sürdürülebilir bitkilendirme alternatiflerinin belirlenmesine katkı sunmaktadır. Elde edilen gözlem sonuçları ve gelişim verileri, nihai rehabilitasyon tasarımında kullanılacak türlerin seçimi ile adaptasyon performanslarının değerlendirilmesinde teknik veri olarak kullanılmaktadır.

Bu yaklaşım sayesinde mühendislik temelli kapatma tasarımı ile ekolojik rehabilitasyon çalışmaları entegre edilmekte ve saha koşullarına uyumlu, uzun vadede doğal dengeyi destekleyen bir iyileştirme planı oluşturulmaktadır. Ayrıca sahadaki flora türlerinin çoğaltılması ve korunması amacıyla farklı bölgelerde bitkisel koruma alanları belirlenmiştir Bitkisel koruma alanları düzenli periyotlarda kontrol edilerek bitki gelişimleri, tohumlanma süreçleri takip edilmektedir. Bunların yanı sıra yılda en az 3 kez Biyoçeşitlilik uzmanları ile birlikte alanlar kontrol edilerek flora kapsamında çalışmalar raporlanmaktadır. Ayrıca Ekim - Kasım aylarında floranın gelişimi için toplanan tohumlar sahada tekrar yetiştirilmek üzere meşe güçlendirme alanında, bitki koruma alanlarında ve botanik bahçede ekimleri yapılmaktadır.

2. Materyal ve Metod

Bu çalışma kapsamında kapatma planlamasına ilişkin değerlendirmeler; laboratuvar deneyleri, kavramsal modelleme çalışmaları ve saha izleme verilerinin birlikte değerlendirildiği entegre bir metodolojik çerçeve içinde yürütülmektedir.

Yığın liçi malzemesine yönelik olarak laboratuvar ölçeğinde kolon deneyleri gerçekleştirilmekte ve oluşan drenaj suyunun kimyasal analiz sonuçları, kapatma sonrası olası jeokimyasal davranışın tahmin edilmesinde kullanılmaktadır. Elde edilen bulgular, örtü tasarımlarının mühendislik kriterleri doğrultusunda karşılaştırılmasına temel teşkil etmektedir.

Alanında uzman danışmanlar tarafından geliştirilen hidrojeolojik ve jeokimyasal kavramsal modeller; saha geometrisi, malzeme karakteristikleri ve su–kayaç etkileşimleri dikkate alınarak oluşturulmakta, farklı kapatma senaryoları bu model altyapısı üzerinden değerlendirilmektedir.

Sahada hâlihazırda sürdürülen yeraltı suyu ve yüzey suyu izleme faaliyetleri ise hem model kalibrasyonu hem de tasarım doğrulaması açısından veri üretmektedir. Pilot kapama uygulamaları, saha ölçeğinde planlanan inşai çalışmalar kapsamında yürütülmekte olup örtü sistemlerinin performansının yerinde gözlemlenmesine imkân tanımaktadır.

3. Bulgular ve Tartışma

Gerçekleştirilen kolon deneyleri, yığın liçi malzemesinin kapatma sonrasındaki uzun dönemli jeokimyasal eğilimlerinin değerlendirilmesine yönelik önemli mühendislik verileri üretmektedir. Bu çalışmalar ile potansiyel drenaj suyunun kimyasal karakteri analiz edilmekte ve örtü tabaka tasarımlarının çevresel performans kriterleri doğrultusunda karşılaştırılmaktadır. Böylece kapatma planlaması, varsayımsal kabuller yerine deneysel sonuçlara ve ölçülebilir parametrelere dayalı bir çerçevede geliştirilmektedir.

Pilot ölçekli örtü uygulamaları ise tasarım yaklaşımlarının saha koşullarında sınanmasına imkân vermektedir. İnfiltrasyon kontrol kapasitesi, yüzey stabilitesi ve su yönetimine ilişkin performans göstergeleri yerinde izlenmekte; elde edilen gözlemler nihai örtü sisteminin performans temelli olarak belirlenmesinde dikkate alınmaktadır. Bu yöntem, maden atıklarının güvenli yönetimine ilişkin ulusal mevzuat gereklilikleri ile uluslararası ölçekte benimsenen kapatma stratejileriyle uyumlu bir planlama anlayışını yansıtmaktadır.

Mühendislik odaklı değerlendirmelere ek olarak rehabilitasyonun ekolojik boyutu da sürece entegre edilmiştir. Bu doğrultuda kurulan Botanik Bahçe aracılığıyla bölgeye özgü endemik bitki türlerinin çoğaltılması ve farklı bitki türlerinin saha koşullarına adaptasyon performanslarının izlenmesi hedeflenmektedir. Elde edilen gözlem verileri, kapatma sonrası arazi kullanımında ekosistemle uyumlu bitkilendirme alternatiflerinin belirlenmesine katkı sunmakta ve rehabilitasyon yaklaşımının yalnızca fiziksel stabilite ile sınırlı kalmayıp ekolojik sürdürülebilirliği de kapsayacak şekilde ele alınmasını sağlamaktadır.

4. Sonuçlar

Bu çalışma kapsamında saha kapatma planlaması; mühendislik tasarımı, jeokimyasal değerlendirmeler ve ekolojik rehabilitasyon bileşenlerinin birlikte ele alındığı entegre bir yaklaşım çerçevesinde incelenmiştir. Laboratuvar ölçeğinde yürütülen kolon deneyleri ile malzemenin uzun dönemli davranış eğilimleri analiz edilmekte, pilot ölçekli örtü uygulamaları aracılığıyla ise tasarımların saha koşullarındaki performansı karşılaştırmalı olarak değerlendirilmektedir.

Elde edilen teknik veriler, kapatma tasarımının yalnızca teorik kabullere dayalı bir planlama süreci olmaktan çıkarılarak ölçülebilir parametreler ve performans göstergeleri üzerinden şekillendirilmesine imkân tanımaktadır. Bu yaklaşım, ulusal mevzuat hükümleri ile uluslararası iyi uygulama prensipleri doğrultusunda sürdürülebilir bir kapatma planlamasının geliştirilmesini desteklemektedir.

Rehabilitasyon sürecinin ekolojik boyutu ise sahada oluşturulan. Bitki koruma alanlarındaki çalışmaları ile güçlendirilmiş; bölgeye özgü flora türlerinin çoğaltılması ve adaptasyon performanslarının izlenmesi sayesinde kapatma sonrası arazi kullanımına yönelik ekosistemle uyumlu bir temel oluşturmaktadır.

Sonuç olarak, yürütülen çalışmalar maden sahalarında kapatma planlamasının yalnızca mühendislik tasarımının yanında; çevresel risk yönetimi, saha koşullarına uyum ve uzun vadeli sürdürülebilirlik perspektifiyle birlikte ele alınması gereken çok disiplinli bir süreç olduğunu ortaya koymaktadır.

Elde edilen tüm izleme ve deney sonuçları, yürürlükteki ulusal ve uluslararası çevresel kalite kriterleri ile uyumlu olup, saha genelinde mevzuat limitlerini aşan bir çevresel etki tespit edilmemiştir

Teşekkür

Bu çalışmanın planlanması ve yürütülmesi sürecinde teknik vizyonu ve sürdürülebilir madencilik yaklaşımıyla Öksüt Madencilik yönetim ekibine teşekkürlerimizi sunarız. Ayrıca, çevresel sorumluluk ve bilimsel temelli kapatma planlaması konularındaki yönlendirici liderliği, stratejik bakış açısı ve teşvik edici yaklaşımıyla çalışmaya değerli katkılar sağlayan Direktörümüz Pelin Usta Özkayhan'a özel teşekkürlerimizi iletiriz. Saha ekiplerimizin özverili çalışmaları ve teknik danışmanlarımızın bilimsel katkıları, bu bütüncül yaklaşımın hayata geçirilmesinde önemli rol oynamıştır.



Progressive Sustainable Rehabilitation of Opencast Mine Drmno External Dump

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Abstract

The widely accepted long-term approach to integrated progressive rehabilitation of opencast mine areas throughout the mining lifecycle, from development to closure, follows the principles of sustainable mining established in international standards and guidelines. Alongside corporate responsibility, the process emphasizes continuous risk assessment, evaluation, and monitoring of environmental impacts, social benefits, and economic factors, while allowing flexibility in post-closure land use to enhance overall outcomes.

For this reason, mine closure and rehabilitation processes must be adaptable so they can respond to changes and risks in a dynamic environment. The aim of this paper is to present and analyze a progressive and adaptable rehabilitation concept for large opencast coal mines that support sustainable land-use transition in line with energy transition and climate policy objectives.

The case study is the rehabilitation of the external overburden dump of the Drmno opencast mine, where the closure plan defined the use of the geomechanically stable area for agricultural activities as a priority, primarily due to strategic principles of the energy transition and climate change. This was successfully expanded in the second phase to include the development of a wind farm on the former overburden waste dump.

Keywords: Energy Transition, Mine Closure, Mine Rehabilitation, Wind Farm

1. Introduction

World best practice shows that integrated mine closure throughout the entire life cycle is necessary to fulfill the principles of sustainable development of surface mining in environmental, social, and economic terms (ICMM, 2019; Demers, 2024). Such an approach minimizes long-term environmental impacts, reduces the final costs of rehabilitation, and enables a more sustainable and integrated approach to managing the mining area, with the possibility of improving and optimizing planning solutions over time (Gagen et al., 2024). In this way, the long-term environmental mining impact is minimized and social and financial risks are reduced (Manero, Standish, & Young, 2021). Planning is carried out in the context of achieving sustainable closure and rehabilitation objectives, with consultations with stakeholders to ensure the successful implementation of reclamation and abandonment of the mining area. Through continuous evaluation and improvement of the effects of all planned activities by means of adaptive management, the maintenance of rehabilitation and closure planning standards is ensured at the operational level as well, along with ongoing risk assessment, management and innovative rehabilitation opportunities (Pavlovic, 2002; Pavlović & Šubaranović, 2012; Pavlovic & Ignjatovic, 2018; Tomlin & Gimber, 2023).

The principles of planning and the conditions for the implementation of surface mine rehabilitation have been addressed in numerous publications and various manuals worldwide (ICMM, 2008; Australian and New Zealand Minerals and Energy Council, 2020; Department of Mines, Petroleum and Exploration, 2025), but the most clearly defined reference is the internationally recognized and recommended standard ISO 21795 – Mine Closure and Reclamation Planning, which contains six framework elements as indicated in Figure 1 (ISO 21795, 2021).

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Figure 1: Mine closure rehabilitation (reclamation) framework (ISO 21795)

They include, as an integral part of the entire mine rehabilitation and reclamation planning process, the company's responsibility, including the engagement of stakeholders, financial management, and securing funds for closure. Planning must be integrated with the management of the socio-economic transition from the opening to the closure of the surface mine. The rehabilitation design process should meet closure and reclamation objectives, with consultation of stakeholders. The risk assessment and management process is necessary for the identification and implementation of options based on opportunities that arise during the mine life cycle. The adaptive management process enables proper evaluation and facilitates continuous improvement throughout the life of the mine. The development, dissemination and preservation of knowledge and data that support the surface mine closure and rehabilitation and reclamation planning process throughout the entire mine life cycle and beyond is of exceptional practical importance.

Such an approach to the rehabilitation process enables efficient and continuous sustainable project implementation, as demonstrated by the example of progressive rehabilitation within the long-term closure planning of the Kostolac coal basin opencast mines (Subaranovic et al., 2018; Faculty of Mining and Geology, 2009).

2. Materials and Methods

All international standards and guidelines recommend that, when planning closure, the mining areas of surface mines should be progressively and integrally rehabilitated as early as possible during the life cycle of the surface mine (Pearce et al., 2016). In this way, a key advantage is provided through continuous practical verification of possible implementation options over time, with the gradual development and improvement of rehabilitation methods. This reduces long-term costs due to improved rehabilitation process outcomes and the reduction of risks associated with the need for reworking poorly rehabilitated areas.

In general, the rehabilitation of surface mines is an expensive process, and financial resources for repeating unsuccessful works are often limited. It is therefore important to consistently adhere to the adopted basic or modified plan in order to achieve acceptable economic results.

The objective of implementing the rehabilitation process is that, after mining, the agreed and designed landform is re-established, contributing to the long-term safety, health, and functionality of the mining area, in accordance with the social, economic, and environmental principles of sustainability, so that the plan includes:

- Minimizing costs and environmental risks, but without affecting the achievement of other long-term objectives;
- Remediation of degraded areas, contaminated soil and water, with an established timeline for the process flow;
- Establishment of sustainable ecosystems;

- Maximizing the use of existing mine infrastructure and the mining area for future optional economic activities;
- Implementation of a safe and sustainable environment aligned with local and regional development plans.

In addition to its direct effects on improving the sustainability of surface mining, progressive rehabilitation enables the implementation and monitoring of the effects of experimental land use. As a rule, it includes basic technical and biological reclamation with possibilities for sustainable modifications as indicated in Figure 2, which has been practically implemented at the Drmno opencast mine. From a planning perspective, it should fulfill four key objectives:

1. Long-term stability and sustainability of landform shapes, soil, and site hydrology;
2. Sustainable usability of the mining area;
3. Partial or complete restoration of the ecosystem’s capacity to provide habitat for biota and services for people; and
4. Prevention of potential pollution and environmental degradation.

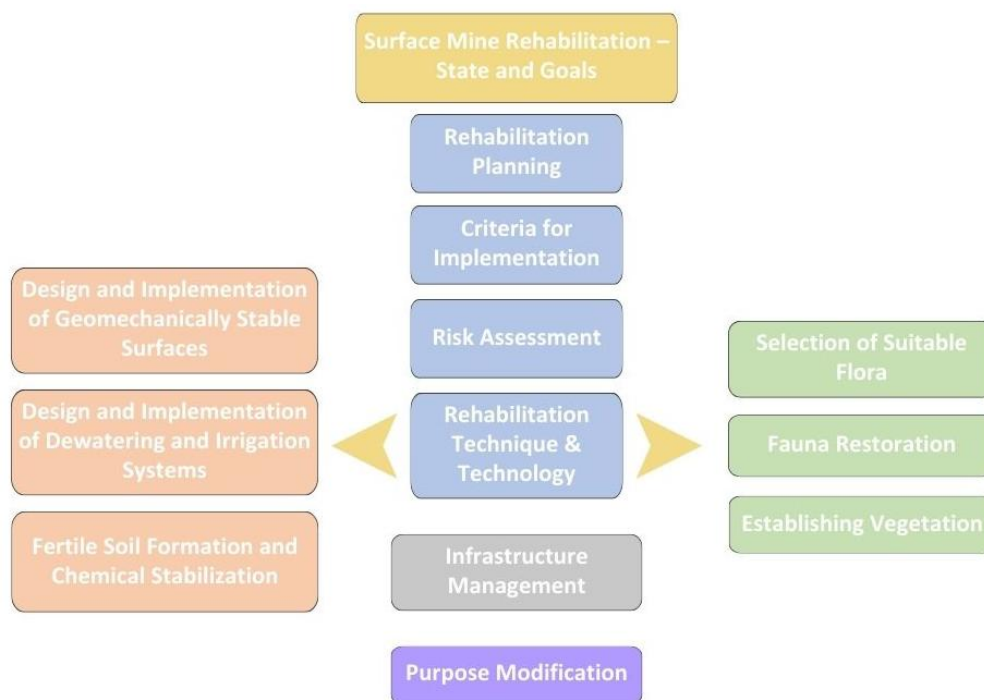


Figure 2: Implementation of a sustainable mine rehabilitation plan

Cost estimates for closure and rehabilitation demonstrate to stakeholders that financial obligations are being actively considered and that risks are well managed during mining operations. This estimate in the early stages of a mine’s life is accompanied by many assumptions and unforeseen events. For this reason, it is essential that closure costs with rehabilitation options are assessed as early as possible in the mine’s life and are continuously adjusted as more knowledge is gained. The process and methodology for calculating cost estimates must be transparent and verifiable, with all assumptions documented (Pavlović & Šubaranović, 2012; Pavlovic & Ignjatovic, 2018).

Landforms are shaped to mimic natural water flow patterns as much as possible, in order to prevent erosion. Where water runoff and infiltration may affect the quality of surface and groundwater, additional protective linings and drainage systems with controlled water flow must be used.

The dynamics of degradation and renewal of the terrain might be defined by degraded and rehabilitated surfaces within a defined moment in time. The coefficient of total rehabilitation can be used as an indicator, with technical and biological recultivation (usually considered separately), representing the ratio of the surface of the renewed terrain at a given moment in time, for example in years or phases (S_{rn}), to the surface of the degraded terrain at that time (S_{dn} , $n = 1, \dots, n$ as the final phase). The coefficient of rehabilitation K_r changes during various mining stages. The rehabilitation state can then be expressed as a function where: $K_r = S_{rn}/S_{dn}$.

At the stage of opening and at the beginning of mining or dumping it is equal to zero, because usually there are no rehabilitation works in this period. During actual mining, with the same progress of works on mining and dumping with recultivation, the coefficient of recultivation might, especially on the external dumps, be equal to one. In the period of closing the surface mine, the degradation of land stops. Then, through recultivation of dumps and final mine boundary, the coefficient of recultivation exceeds one. The surface of renewed external and internal dumps could cover 80 to 85% of degraded surface and thus the coefficient of recultivation from 0.8 to 0.85 refers to agricultural and forestry terrain. The remaining part of the total degraded surface area could be flooded and utilized for fishing and recreation and tourism (Pavlovic, 2002).

The set recultivation system connected to the effect of the surface mining on land degradation can, in theory, have three states (E_0, E_1, E_2). The normal state of the rehabilitation/recultivation system is denoted by E_0 ; state E_1 represents a condition in which the process realization time is at risk but still within permitted limits, while state E_2 represents an extreme failure condition in which the realization time exceeds the permitted limits. Then, a more active recultivation causes a decrease in degradation and transfers the system from situation E_2 into situation E_1 and further into situation E_0 (Pavlovic & Ignjatovic, 2018).

For the calculation of the probabilities and risks of rehabilitation realization, the functioning of the rehabilitation system can be presented as a Markov stochastic process with discrete states for all possible states. Assuming exponentially distributed failure and renewal times for each state, transition intensities (a) and (b) have mean time to failure ($T_f = 1/a$) and mean time to renewal ($T_r = 1/b$). In this way, a graph of three states is formed in the shape of a chain as indicated in Figure 3.

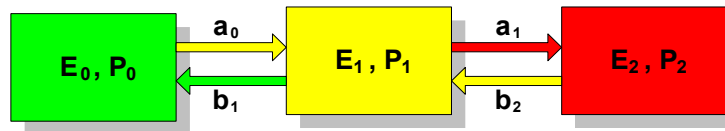


Figure 3: Directed graph of the rehabilitation process with three states

For this process, the limiting probabilities of states are expressed by the following formulas:

$$P_0 = \frac{1}{1 + \frac{a_0}{b_1} + \frac{a_0 a_1}{b_1 b_2}} \tag{1}$$

$$P_1 = \frac{a_0}{b_1} P_0 \tag{2}$$

$$P_2 = \frac{a_0 a_1}{b_1 b_2} P_0 \tag{3}$$

the sum total of which equals one. On the basis of the total probability, the rehabilitation probabilities under the criteria of occurrence of the extreme situation (system failure) are determined and are as follows: $P_2 = 1 - P_0 - P_1$.

3. Results and Discussion

Opencast coal mine Drmno, which is working as a part of the state-owned Joint Stock Company Elektroprivreda Srbije (Electric Power of Serbia), is located south of the southern bank of the River Danube, about 65 km east of Belgrade, with an annual output of $9 \cdot 10^6$ tonnes of coal. A medium-sized external dump is situated east of the Drmno opencast mine, spreading over around 200 ha as indicated in Figure 4. Dumping was finished in 2000, and rehabilitation began with the removal of the main equipment and shaping of $75,000,000 \text{ m}^3$ of overburden material. After that, ecorecultivation was selected for recultivation by the Project (Faculty of Mining and Geology, 2009) on the degraded terrain created by the dumping at the external dump.

Final reclamation of the dump, as part of the planned rehabilitation, is implemented in two distinct phases. The first progressive phase refers to the execution of the original mine closure and rehabilitation plan, which aimed to restore the external dump to a condition suitable for agricultural production, grazing lands, and meadows. The second phase covers changes in the reclamation process resulting from the subsequent decision to construct a wind park on the dump site, with planned full completion by 2026.

In accordance with the original recultivation concept, the external dump was meliorated to a state suitable for agricultural use. Existing surfaces have been given a shape that ensures ecologically favorable integration

of these surfaces with the environment, and conditions have been created for biological recultivation to the extent that the available dumping technology makes possible.

By engineered measures of technical recultivation, conditions are met for the final forming of surfaces of the external dump. The preparation of the dump for biological recultivation is done through leveling horizontal and slightly inclined surfaces with the appropriate slope for water drainage. Reforestation is planned for the steeper slopes. Recultivation according to the original plan was completed in five years, after which modifications were introduced in the second phase. Technical recultivation includes earthworks as well as engineering measures such as drainage and infrastructure development, forming the basis for subsequent biological recultivation. It consists of the following number of measures and actions:

- Leveling and shaping of flat surfaces at external dump benches;
- Shaping of external dump slopes;
- Fine leveling of external dump surfaces;
- Construction of channels and lakes for dewatering and irrigation of the external dump, and
- Construction of access and internal roads.

Throughout the recultivation works, the terrain, weather, and technological parameters have been monitored in order to ensure control of risks related to process realization, scheduling, and planning. Results of these measurements and monitoring, with probability of states, as presented in Table 1.

Table 1: Change of parameters in the external dump recultivation system

Recultivation completion	2010	2011	2012	2013	2014	2015
Planned Area (2*10 ⁶ m ²)	274,000	708,000	510,000	258,000	250,000	(112,500)
<i>Technical recultivation (%)</i>						
Current year	75	70	80	20	55	
From previous year	-	25	30	20	80	45
<i>Biological recultivation (%)</i>						
Current year	70	60	50	10	05	
From previous year	-	30	40	50	90	95
K _r	0.096	0.350	0.619	0.759	0.881	1
a ₀	0.01	0.02	0.05	0.12	0.02	0.01
a ₁	0.02	0.03	0.05	0.18	0.03	0.03
b ₁	0.03	0.05	0.11	0.08	0.09	0.05
b ₂	0.06	0.09	0.08	0.06	0.11	0.06
P ₀	0.69	0.65	0.58	0.14	0.78	0.77
P ₁	0.23	0.26	0.26	0.22	0.17	0.15
P ₂	0.08	0.09	0.16	0.64	0.05	0.08

The results indicate a clear improvement in system stability over time, as reflected in the increase of the probability of the normal operating state P₀, which reached values of up to 0.78–0.77 in the final years of recultivation. At the same time, the probability of extreme failure P₂ remained low, except for a temporary

increase in 2013 (0.64), which corresponds to delays in the implementation phase. Following corrective technical measures, the system rapidly returned to stable conditions.

Throughout the entire planned lifespan of the rehabilitation of the external dump, implementation risks remained high, with significant consequences and losses, primarily due to delays in execution (2013) and the realization of the progressive rehabilitation plan for the dump in the second phase (2015).

The system operating probability reached up to 80% following corrective interventions, so that all planned works were successfully completed on schedule in 2015, with the recultivation of the remaining dump surface of 112,500 m², mainly due to the auxiliary construction works of the wind park. The appearance of the completed external dump of the opencast mine Drmno with the layer of humus is shown in Figure 4. Total costs for the recultivation works of the external dump are €3,254,000.



Figure 4: Final rehabilitation phase of the external dump

Since it was proven that there is no risk of liquefaction on the well-stabilized external dump, the remaining areas were subsequently designated for the construction of a wind park, including full infrastructure, which led to a general revision of the final rehabilitation plan in the second progressive phase [8]. By 2024, internal access roads and foundations for seven wind generators, each with a capacity of 3.3 MW, were constructed as indicated in Figure 5. Final works were being carried out in 2025, and successive trial operations of the wind park started in December 2025.



Figure 5: Constructed wind park on the external dump

The application of the Markov model enabled quantitative assessment of rehabilitation risks and demonstrated that timely technical interventions significantly reduce the probability of system failure. The

construction of the wind park was carried out on a stabilized and fully recultivated dump surface without compromising its geotechnical stability, as a progressive rehabilitation solution.

4. Conclusion

Climate change and the energy transition have driven a global increase in the exploitation of mineral resources and the expansion of surface mining areas, while also presenting mining companies with significant ecological, social, and economic challenges. Consequently, alongside detailed assessments, growing attention is being given to progressive, modified processes, facilities, and technologies for the rehabilitation of surface mines as integral components of new projects. In accordance with widely accepted standards, continuous integrated management is essential, encompassing ongoing monitoring of environmental impacts, social and financial risks, and the implementation dynamics of surface mine rehabilitation plans.

This approach has demonstrated positive, sustainable, and adaptable outcomes in the progressive two-phase rehabilitation of the external dump of the Drmno opencast mine in Serbia, successfully supporting both agricultural use and subsequent development of a wind farm. The results show that integrating progressive closure planning with a Markov-based risk assessment framework allows early identification of rehabilitation delays and instability, enabling timely corrective actions and reducing long-term closure risk. The study also confirms that properly executed recultivation can support safe transition to alternative land use, including wind energy development.

Acknowledgments

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Terkedilmiş Mermer Sahasının (Burdur) Rehabilitasyonunun Araştırılması, Özelliklerinin Belirlenmesi ve Değerlendirilmesi

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Özet

Bu çalışmanın temel amacı, açık mermer ocaklarının peyzaj ve topoğrafya üzerinde yarattığı tahribatı azaltmak için Burdur ili Yeşilova ilçesinde bulunan terk edilmiş bir açık mermer ocağında örnek bir rehabilitasyon projesi geliştirmektir. Arazi çalışmaları kapsamında İHA ile sayısal yükseklik modeli oluşturulmuş, göletin batimetrik haritası çıkarılarak derinliğin 9,6 metre olduğu tespit edilmiştir. Çevresel durumu belirlemek amacıyla toprak, sediman ve su numuneleri alınmış, majör oksit ve ağır metal kirlilik düzeyleri incelenmiştir. Ağır metal varlığının antropojenik değil, bölgedeki ofiyolitik kayaçların jeokimyasından kaynaklandığı ve su kalitesinin tarımsal ve rekreasyonel kullanıma uygun olduğu görülmüştür. Ayrıca, sahada bulunan 137.886 m³ mermer pasasının agrega ve farklı endüstrilerde hammadde olarak yeniden kullanılabilirliği kanıtlanmıştır. GZFT ve ekosistem değerlendirme analizleri sonucunda, alanın doğal potansiyeli göz önüne alınarak bir "Arkeopark" olarak tasarlanması önerilmiş ve peyzaj senaryoları modellenmiştir.

Anahtar Kelimeler; Maden Sahası Rehabilitasyonu, Ekosistem Değerleme, Uzaktan Algılama, Arkeopark, GZFT

Investigation, Characterization, And Assessment Of The Rehabilitation Of An Abandoned Marble Quarry (Burdur)

Abstract

The main objective of this study is to develop a rehabilitation project in an abandoned open marble quarry located in Burdur province, Yeşilova district, to reduce the destruction caused by mining on the landscape and topography. A digital elevation model was created via UAV, and the bathymetric map of the pond revealed a maximum depth of 9.6 meters. Soil, sediment, and water samples were analyzed for major oxide and heavy metal pollution. Results showed that heavy metal presence originates from the geochemistry of ophiolitic rocks rather than anthropogenic sources, and the water quality is highly suitable for agricultural and recreational use. Furthermore, 137,886 m³ of marble waste is proven reusable in various industries. Based on SWOT and ecosystem valuation analyses, the site is recommended to be designed as an "Archaeopark".

Keywords: Mine Rehabilitation, Ecosystem Valuation, Remote Sensing, Archaeopark, SWOT

1. Giriş

Maden Tetkik ve Arama (MTA) Genel Müdürlüğü Çevre Araştırmaları Dairesi, 2010 yılından bu yana bilimsel araştırma programları kapsamında sürdürülebilirlik prensibini ve toplumsal refahı temel alan kapsamlı rehabilitasyon projeleri yürütmektedir. Kurumumuzun bu alandaki köklü tecrübesinin bir yansıması olarak, geçmiş yıllarda Muğla'da Türkiye Kömür İşletmeleri'ne (TKİ) ait Yeniköy Linyitleri İşletmesi Yaylıktepe pasa sahasında ve Manisa-Soma'da Ege Linyitleri İşletmesi Işıklar pasa sahasında benzer nitelikte doğaya yeniden kazandırma projeleri başarıyla hazırlanmıştır. Uluslararası teknik standartlara uygun olarak geliştirilen bu projeler detaya inildiğinde; fiziksel, kimyasal ve peyzaj onarımını kapsayan 'teknik analiz' ile alanın yaratacağı net toplumsal faydayı ölçen 'ekonomik değerlendirme' olmak üzere iki temel bileşen üzerine kurgulanmaktadır. Kurumumuzun Soma ve Muğla projelerinde elde ettiği bu güçlü birikim ve multidisipliner yaklaşım, Burdur'da yürüttüğümüz mermer ocağı rehabilitasyon projesinin de sağlam bir temelini oluşturmaktadır.

Madencilik faaliyetleriyle bozulan ekosistemin onarılması sorunu günümüzde sürdürülebilirlik ve rehabilitasyon kapsamında ele alınmaktadır. Madenlerin doğaya yeniden kazandırılması, çevresel bozulmayı minimize ederken arazinin ekolojik olarak dengeli ve verimli biçime dönüştürülmesini sağlar (Demirbugan, 2019a; Down & Stocks, 1977). Burdur ili Yeşilova ilçesi Çaltepe köyünde bulunan terkedilmiş açık mermer ocağı, Salda Gölü ve tarihi kaya mezarlarına yakınlığı nedeniyle önemli bir rekreasyonel potansiyele sahiptir. Turizm potansiyelinin yüksek olması rehabilitasyon çalışmalarının başarısı açısından oldukça değerlidir. Bu çalışmada, söz konusu sahanın çevresel parametreleri ve rehabilitasyon potansiyeli multidisipliner bir yaklaşımla araştırılmış, bölgenin çevresel, hidrojeolojik ve peyzaj dinamikleri incelenmiştir.

Burdur ilinin "**ekonomik gelişiminin dinamosu**" olarak nitelendirilen sektör mermerciliktir ve bölgede çıkarılan "**Burdur Beji**" dünya doğal taş sektöründe önemli bir markaya ve yere sahiptir. Burdur Beji mermerinin ve genel olarak doğal taş üretiminin bölge ekonomisindeki doğrudan payı şu temel göstergelerle ifade edilebilir:

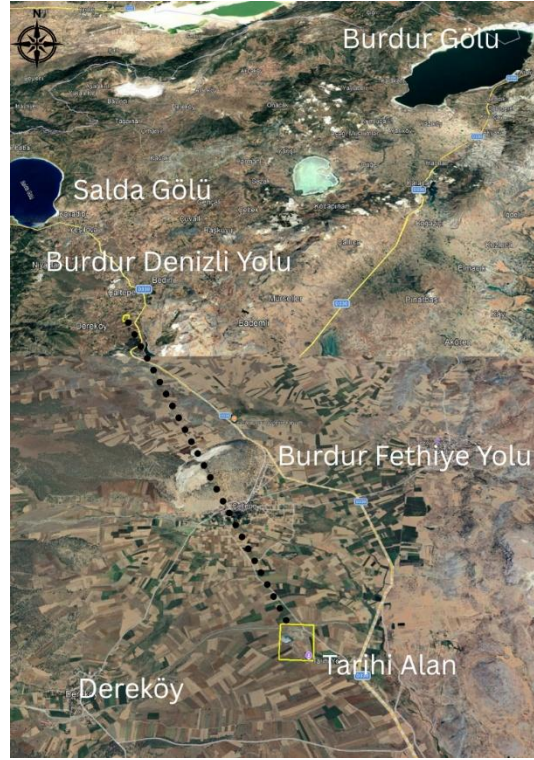
- **İhracattaki Büyük Pay:** 2012 yılı verilerine göre madencilik ürünleri, Burdur ilinin imalat ihracatının **%40'ını** tek başına karşılamıştır (World Bank, 2016). Ayrıca 2022 yılı TÜİK verilerine göre de ilin ihraç ettiği ürünlerin en başında doğal taş ve yan ürünleri gelmektedir.
- **Üretim ve Satış Kapasitesi:** Burdur'daki mevcut mermer üretiminin büyük bir kısmı olan **%85'i doğrudan ihraç edilmekte**, geriye kalan **%15'lik** kısım ise iç piyasada satılmaktadır (Kalkan, 2018).
- **Yüksek İstihdam Oranı:** Bölgede 184 adet aktif olarak çalışan mermer ocağı ile 124 adet mermer fabrikası ve atölyesi bulunmaktadır. Bu işletmeler, Burdur ilinde **9.000'den fazla kişiye** iş imkânı sunmaktadır. Bu sayı, ildeki **toplam istihdam değerinin üçte birine** (1/3) karşılık gelerek bölge halkı için hayati bir gelir kaynağı oluşturmaktadır.

Mermer, doğal taş ekonomisi ve sanayisi, yarattığı bu geniş ticaret hacmi ve yüksek istihdam kapasitesiyle Burdur il ekonomisine en büyük katkıyı sağlayan sektördür.

2. Çalışma Sahası

Çalışma alanı, Burdur ili Yeşilova ilçesindeki Dereköy ile Çaltepe köyleri arasında bulunan (Şekil 1) ve önceden açık işletme yöntemi ile işletilmiş terkedilmiş bir mermer ocağıdır. Ruhsat alanında yer alan bu sahanın içerisinde, yeraltı sularının birikmesiyle oluşmuş yaklaşık 150x110 metre ebatlarında bir gölet bulunmaktadır.

Coğrafi olarak Göller Yöresi'nin batısında yer alan sahanın rehabilitasyonu için konumundan ve ekolojik altyapısından kaynaklanan pek çok avantajı bulunmaktadır. Yılda yaklaşık 1,5 milyon turist ziyaret ettiği turkuaz renkli Salda Gölü'ne sadece 15 km mesafede olması ve turizm yoğunluğunun yüksek olduğu Burdur-Fethiye (7 km) ile Burdur-Denizli (12 km) karayollarına yakınlığı alanın ulaşılabilirliğini ve turistik cazibesini artırmaktadır. Sahanın sadece 400 metre güneyinde yer alan antik kaya mezarları (gavur damı) gibi arkeolojik kalıntılar ile ocak içindeki hidrolojik oluşumun (göletin) bir arada bulunması, bu alanın kültür ve doğa turizmini harmanlayan bir "Arkeopark" konseptiyle değerlendirilmesine büyük bir potansiyel sağlamaktadır. Bunlara ek olarak, madencilik faaliyetlerinden arta kalan mermer pasalarının (artıklarının) alandan başka bir yere taşınmasına gerek kalmadan, doğrudan yerinde inşa edilecek rekreasyonel ve mimari yapılarda kullanılabilir olması çok önemli bir avantajdır (Şekil 2).



Şekil 1: Çalışma sahasının yer bulduru haritası



Şekil 2: Çalışma sahasının bulunan pasalar ve arkeolojik kalıntılar

3. Çalışma Sahasının Jeolojisi

Türkiye'nin güneybatısında (Batı Toroslar) Burdur ili sınırları içerisinde yer alan çalışma alanının (Şekil 1) jeolojisi; alttan üste doğru otokton konumlu Beydağları otoktonu, allokton konumlu naplar (Antalya, Yeşilbarak ve Likya napları) ile paraallokton ve neotokton konumlu örtü kayalarından oluşmaktadır. Sahanın genelinde Marmaris Peridotiti, Kızılcaadağ Melanj ve Olistostromu, Dutdere Kireçtaşı, Mamatlar Formasyonu, Varsakyayla Formasyonu ve Çameli Formasyonu yüzeylemektedir (Şekil 3).

Çalışma alanı ve çevresindeki temel jeolojik birimler şu şekildedir:

Bodrum Napı: Bölgedeki en alt yapısal birimdir ve Mallıdağ, Akgöl ile Ören birimleriyle temsil edilir.

Marmaris Ofiyolit Napı: Bodrum napının üzerinde yer alan bu birim, Marmaris Peridotiti ve Kızılcaadağ Melanj ve Olistostromu ile temsil edilir.

Marmaris Peridotiti: Çapan (1980) tarafından adlandırılmış olup, çoğunlukla serpantinit, peridotit (ağırlıklı olarak harzburgit), piroksenit ve dunitlerden oluşur. Birimin oluşum yaşı Thuizat vd., (1981) tarafından Apsiyen-Albiyen olarak belirlenmiş olup, bölgeye yerleşimi Şenel vd. (1996) tarafından Geç Senoniyen olarak ifade edilmiştir.

Kızılcaadağ Melanj ve Olistostromu: Poisson (1977) tarafından tanımlanan bu karmaşık yapı; serpantinit, radyolarit, çört ve pelajik/neritik kireçtaşı bloklarını kapsar. Şenel vd., (1996) birimin oluşum yaşını Geç Senoniyen (Kampaniyen-Maastrichtiyen) olarak kabul etmektedir.

Gülbahar Napı: Ofiyolit napının üzerinde bulunur ve Meşhur vd., (1989) tarafından adlandırılan, Jura-Kretase yaşlı Orhaniye Formasyonu'nu (çörtlü mikritler, bazik volkanitler ve radyolaritler) içerir.

Domuzdağ Napı ve Dutedere Kireçtaşı: Likya naplarının en üst yapısal birimidir. Ersoy (1989,1990) tarafından adlandırılan Dutedere Kireçtaşı ile temsil edilir. Orta Triyas-Liyas yaşlı bu kireçtaşları, 700 metre kalınlığa ulaşabilen masif, rekristalize karbonatlardan oluşur, Alanın temel ekonomik değeri olan "Burdur Beji" mermeri, bu formasyon içerisindeki kireçtaşlarından elde edilmektedir.

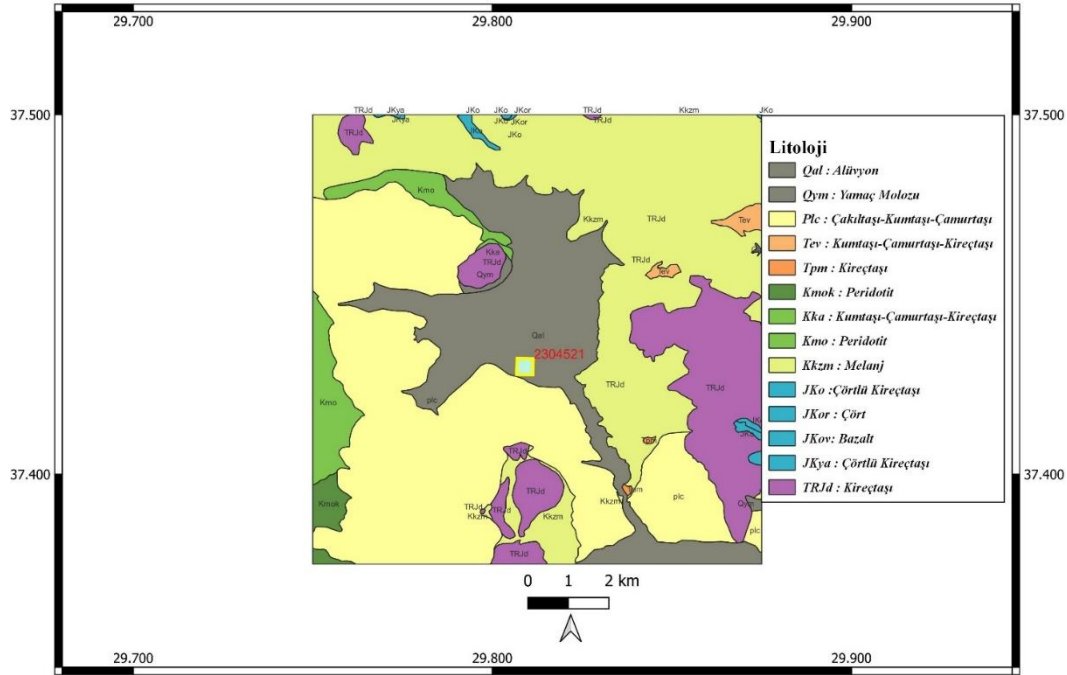
Karaböğürtlen Formasyonu: Philipson (1915) tarafından adlandırılan Geç Senoniyen yaşlı bu formasyon, tabanında kalsitürbiditler içeren ve bloklu fişlerle temsil edilen kaotik bir yapı sunar. Formasyonun yaş ve çökme özellikleri Sarp (1976) ve Şenel vd. (1996) tarafından da araştırılmıştır.

Mamatlar Formasyonu: Şenel vd., (1989) tarafından tanımlanmıştır. Likya napları üzerinde açılal uyumsuzlukla oturan, Geç Paleosen yaşlı sığ şelf ortamı çökeli olan bol algli kireçtaşlarından oluşur.

Varsakyayla Formasyonu: Poisson (1977) tarafından adlandırılan bu formasyon, türbiditik karakterli kumtaşı, silttaşı ve polijenik konglomeralardan oluşur. Geç Lütésiyen-Priyaboniyen yaşlıdır (Şenel vd., 1989).

Çameli Formasyonu: Erakman, vd., (1982) tarafından adlandırılmıştır. Geç Miyosen-Pliyosen yaşlı bu formasyon, karasal alüvyon yelpaze çökelleri ve gösel karakterde kıltaşı, marn, kumtaşı gibi kırıntılılardan meydana gelir (Göktaş vd., 1989).

Kuvaterner Çökelleri: Sahada en üst örtü birimi olarak dağ eteklerinde yamaç molozları (Qym) ve akarsu yataklarındaki düzlüklerde güncel alüvyon (Qal) birikintileri bulunur



Şekil 3: Çalışma sahasının jeoloji haritası

3. Materyal ve Metot

Çalışma alanının mevcut çevresel durumunu ve morfolojisini belirlemek amacıyla İHA ölçümleriyle sayısal yükseklik modeli (DEM) ve topoğrafik haritalar oluşturulmuş, eski işletme basamaklarında oluşan göletin batimetrik etüdü tek ışınlı derinlik ölçer cihazlarıyla gerçekleştirilmiştir. Kimyasal kirliliği belirlemek üzere sahayı ve tampon bölgeleri temsil eden 25 adet toprak ve dere sedimanı ile 20 adet su numunesi alınarak XRF ve ICP-OES analizlerine tabi tutulmuştur. Ağır metal kirliliğini değerlendirmek için Turekian ve Wedepohl (1961) tarafından belirlenen dünya şeyl ortalamaları kullanılarak Zenginleşme Faktörü (*Ef*), Jeobirikim İndeksi (*Igeo*), Kirlilik Faktörü (*Cf*) ve Kirlilik Yükü İndeksi (*PLI*) hesaplanmıştır. Sosyo-ekonomik ve stratejik değerlendirme için ise GZFT analizi ve ekosistem değerlendirme yöntemleri uygulanmıştır.

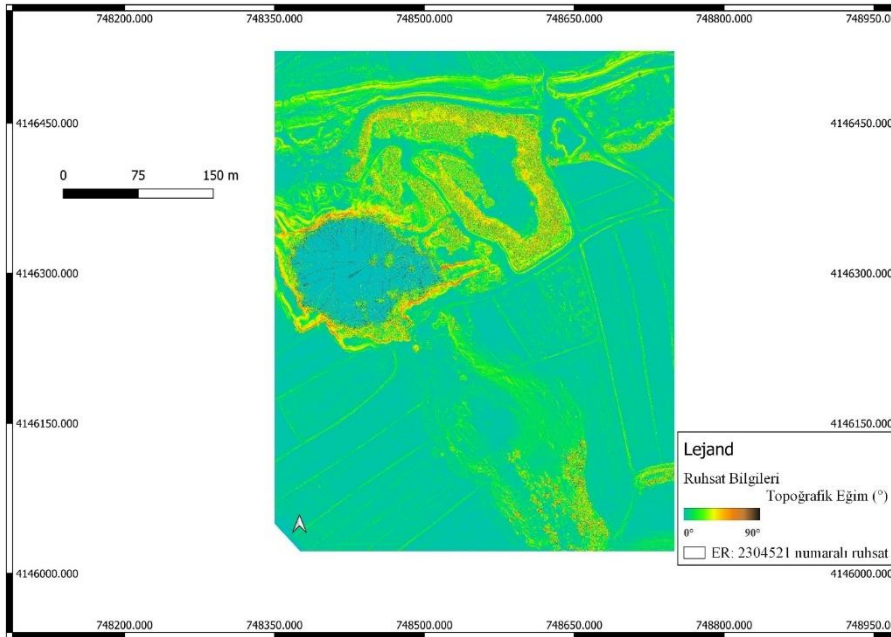
Peyzaj mimarlığı ve doğa onarımı çalışmaları kapsamında, öncelikle faaliyetini sonlandırmış mermer ocağının güncel durumunu, fiziksel ve çevresel özelliklerini belirlemek amacıyla detaylı alan analizleri gerçekleştirilmiştir. Bu analizler doğrultusunda; topoğrafik yapı, hâkim rüzgâr, güneşlenme yönü, su ögesi (gölet) ve alanın hemen güneyinde yer alan arkeolojik sit alanı gibi veriler çakıştırılarak alanın tasarım potansiyelleri saptanmıştır. Tespit edilen potansiyellere göre ziyaretçi gereksinimlerini karşılayacak bir ihtiyaç listesi (otopark, kafeterya, müze, çadır kamp alanı, seyir terasları vb.) belirlenmiş ve bu kullanımların mekânsal dağılımını gösteren leke paftaları oluşturulmuştur. Sahanın rehabilite edilmesi amacıyla bilgisayar destekli modelleme programları kullanılarak 21 farklı peyzaj senaryosu üretilmiş; alanın tarihi kaya mezarlarına ve arkeolojik kalıntılara yakınlığı sebebiyle “Arkeopark” konsepti temel alınarak leke paftaları ölçekli bir avan projeye dönüştürülmüştür

Çalışma sahasının rehabilite edilebilirliğini ekonomik boyutuyla incelemek amacıyla GZFT (SWOT) analizi, ekosistem değerlendirme ve ticari karlılık analizlerini kapsayan bütünlük bir değerlendirme yöntemi izlenmiştir. Stratejik planlamanın bir parçası olarak uygulanan GZFT analizi ile alanın iç çevre faktörleri (güçlü ve zayıf yönler) ile dış çevreden kaynaklanan koşullar (fırsat ve tehditler) sistematik olarak tespit edilmiştir. Çevresel varlıkların madencilik sürecindeki değişiminin toplumsal refaha etkisini ölçmek için “Toplam Ekonomik Değer (TED)” yaklaşımına dayalı ekosistem servis değerlemesi yapılmıştır. Bu hesaplamalarda, küresel ekosistem servis birim değerleri “fayda transferi yöntemi” kullanılarak enflasyon oranları ve kişi başına düşen milli gelir esnekliği bazında yerel koşullara uyarlanmıştır. Önerilen peyzaj ve rekreasyon projesinin (ÇDRP) finansal uygulanabilirliğini belirlemek amacıyla ise cari piyasa fiyatları üzerinden ticari karlılık analizi gerçekleştirilmiş; projenin yatırım maliyetleri ve işletme gelirleri ilişkilendirilerek Fayda/Maliyet oranı (F/M), Basit Karlılık Oranı (BKO) ve Geri Ödeme Süresi (GÖS) gibi temel karlılık ölçütleri hesaplanmıştır.

4. Bulgular ve Tartışma

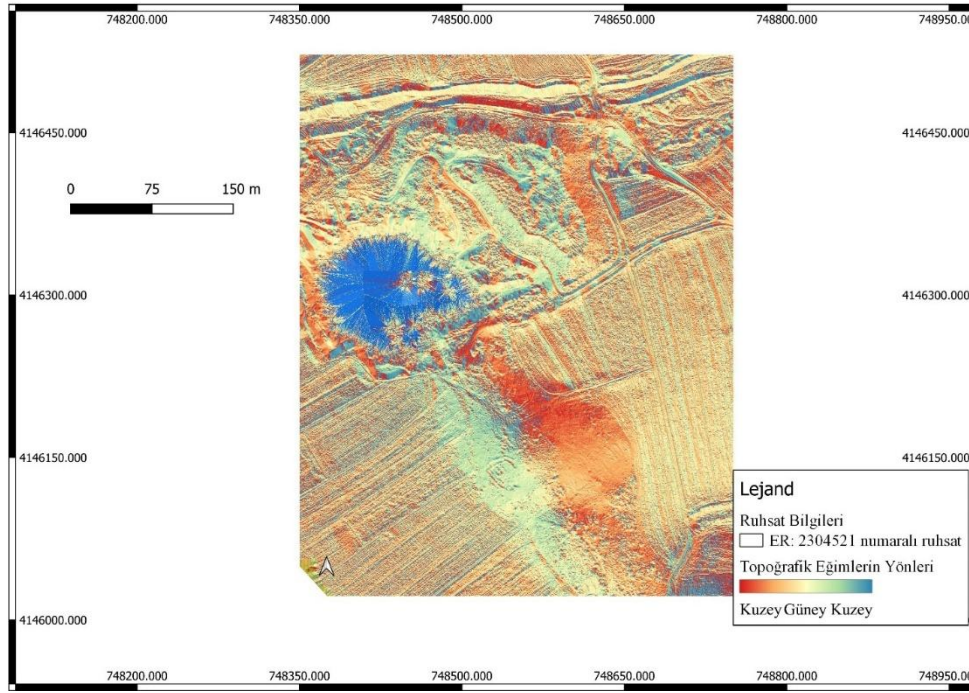
Çalışma kapsamında İnsansız Hava Aracı (İHA) uçuş verilerinden elde edilen 2 cm çözünürlüklü Sayısal Yükseklik Modeli (DEM) kullanılarak alanın topoğrafik karakteristikleri modellenmiştir. Coğrafi Bilgi Sistemleri (QGIS) yazılımı üzerinden işlenen bu veriler yardımıyla sahanın topoğrafik eğim, eğim yönü, topoğrafik ayırım kümelenmeleri ve alt havza haritaları üretilmiştir.

Üretilen topoğrafik eğim haritası incelendiğinde, rehabilitasyon projesi kapsamında alana kurulması planlanan güneş enerjisi panelleri için yer seçimi değerlendirilmiştir. Panellerin birbirini gölgelememesi ve verim kaybı yaşanmaması adına 0-30 derece arası eğimler ideal kabul edilmiş olup, mermer sahasının batı kısımlarında bu koşulları sağlayan uygun eğimli alanlar tespit edilmiştir (Şekil 4).



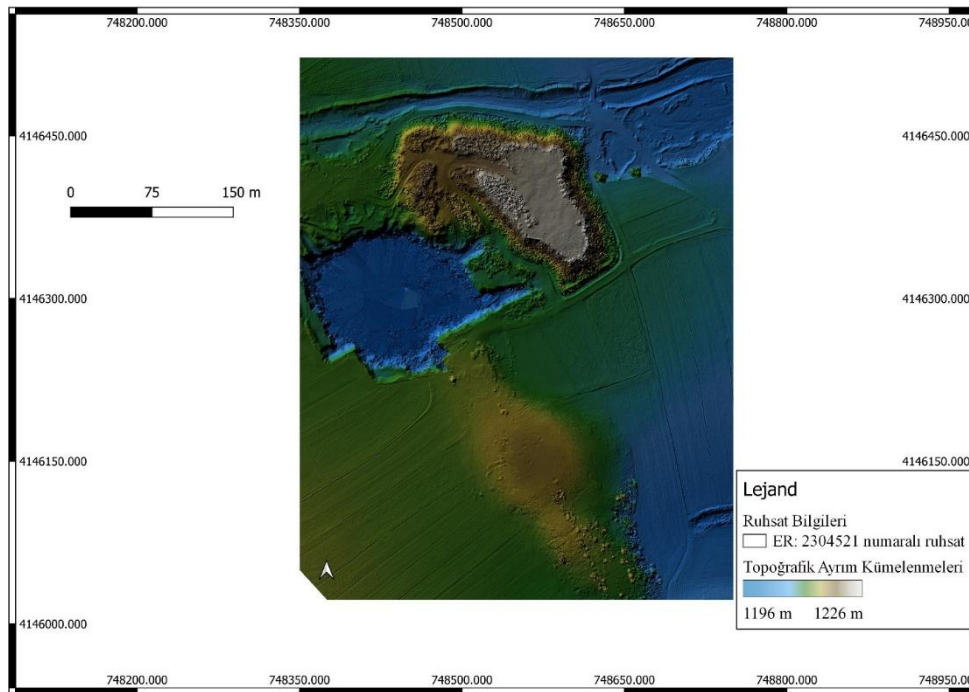
Şekil 4: Çalışma sahasının topoğrafik eğim haritası

Bununla birlikte, DEM verilerinin içerdiği yükseklik bilgileriyle oluşturulan topoğrafik eğim yönü haritasına göre, güneş paneli yerleşimi için en verimli yön olan güneye bakan uygun eğimli topoğrafyanın yine ocağın batı kısımlarında yoğunlaştığı doğrulanmıştır (Şekil 5).



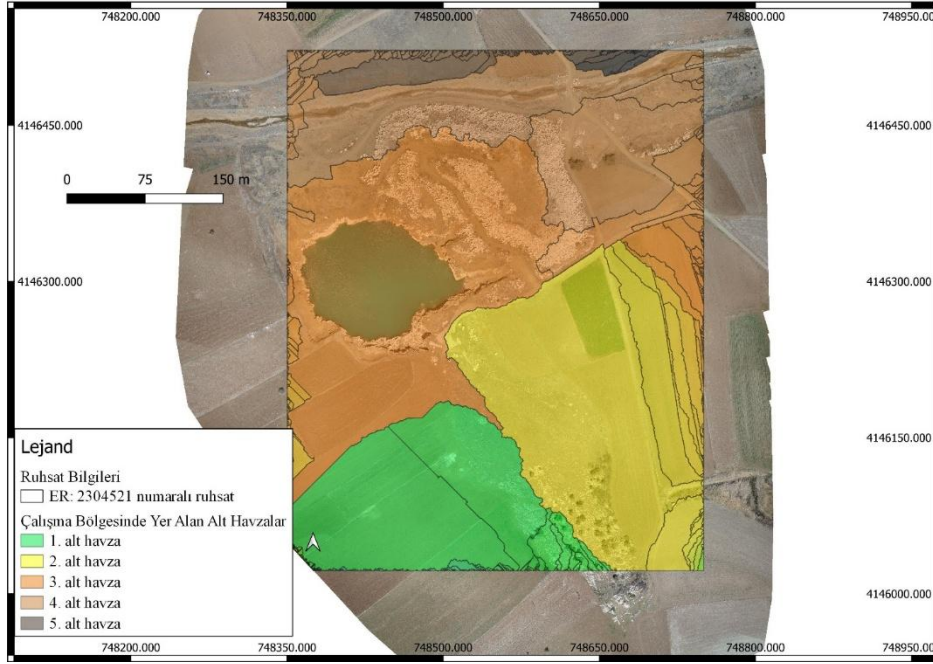
Şekil 5: Çalışma Sahasının topoğrafik eğim yönleri haritası

Çalışma bölgesindeki morfolojik yapıların sınıflandırılması amacıyla topoğrafik ayırım kümelenmeleri çalışılmıştır. Analiz sonucunda alanda üç ana topoğrafik ayırım saptanmıştır: Ruhsat içerisindeki gölet ve doğal sulama kanallarından oluşan su kütleleri, tarla olarak kullanılan alanlar ve mermer artıklarının bulunduğu pasa yığınlarıdır (Şekil 6).



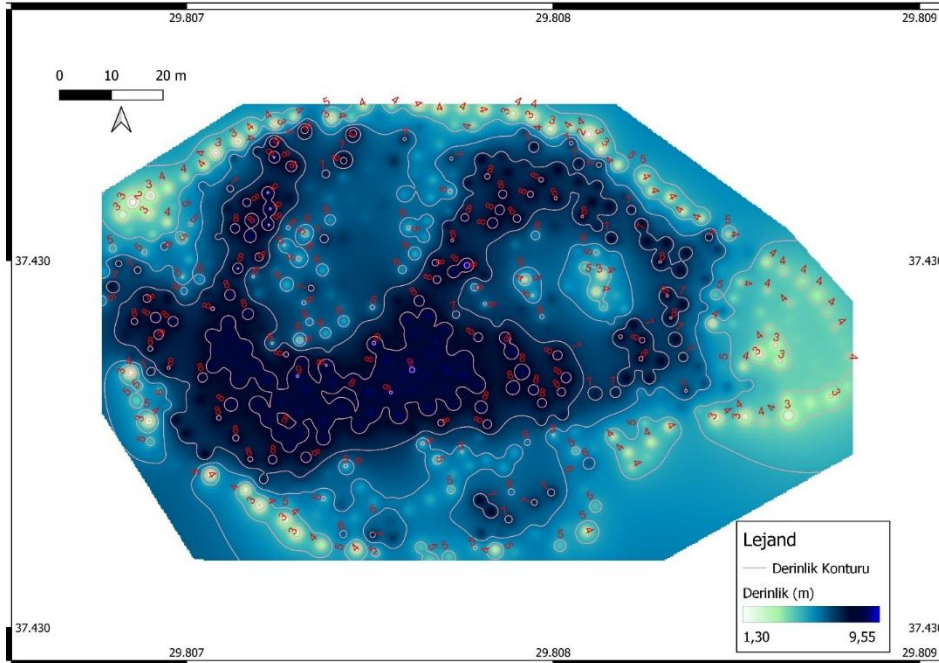
Şekil 6: Çalışma sahasının topoğrafik ayırım kümelenmeleri haritası

Hidrolojik değerlendirmeler kapsamında ruhsat alanı içerisindeki su ayırma çizgileri (alt havzalar) belirlenmiş ve alan içerisinde toplam 5 adet alt havza olduğu saptanmıştır. Rehabilitasyon araştırmalarının odak noktası olan ve ocak bölgesini kapsayan ana alt havzanın yaklaşık 5 hektar büyüklüğünde olduğu hesaplanmıştır. Bu havzanın negatif rölyefinin tabanı doğrudan ocak çukurunda yer almakta olup, alandaki yüzey akışlarının yönünün ocağa doğru olduğu belirlenmiştir (Şekil 7). Ocak içerisinde bulunan su kütlesi ağırlıklı olarak yeraltı suyuyla beslense de topoğrafik eğim ve havza sınırları sebebiyle az da olsa yer üstü besleniminin de hidrolojik bütçeye katkı sağladığı görülmektedir.



Şekil 7: Çalışma bölgesinde yer alan alt havzaları gösterir harita

Batimetrik ölçümler sonucunda ocak içindeki göletin en derin noktasının 9,6 metre olduğu, genel derinliğin ise 3 ila 9 metre aralığında değiştiği tespit edilmiştir (Şekil 8).



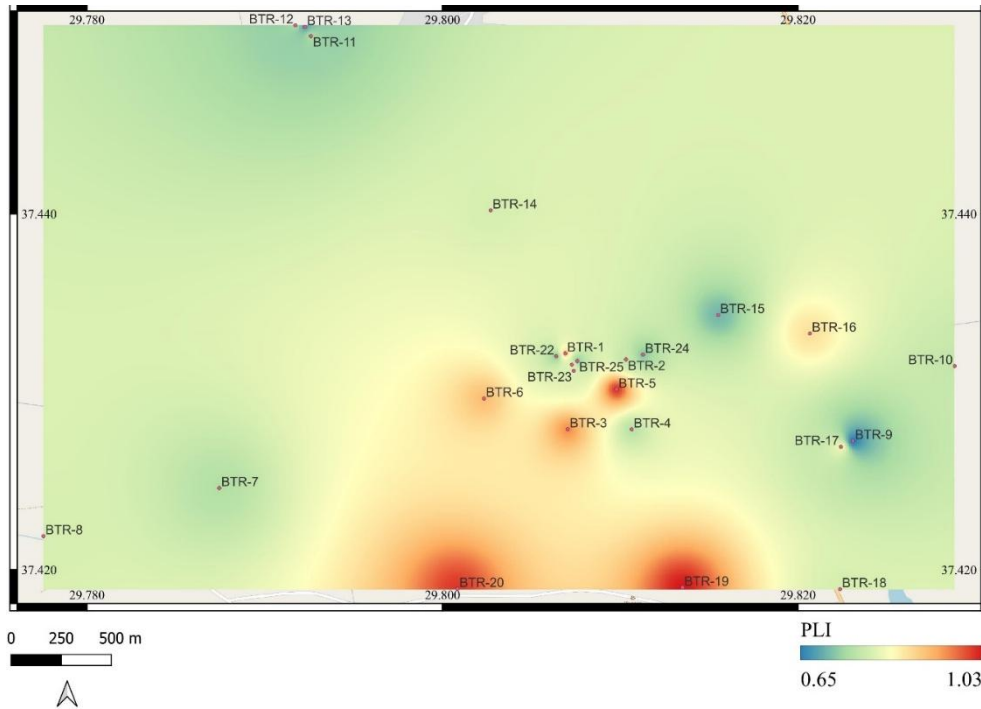
Şekil 8: Çalışma bölgesinde yer alan ocağın batimetri haritası

İHA verileri kullanılarak hesaplanan 137.886 m³ (yaklaşık 366.227 ton) mermer 91aşasının, fiziksel ve kimyasal uygunluğu incelendiğinde; şeker sanayii, lastik-kauçuk sektörü ve çeşitli inşaat agregaları (dolgu ve asfalt karışımı) olarak kullanıma uygun olduğu tespit edilmiştir (Çizelge 1). Atıkların bu şekilde değerlendirilmesi, madencilik sonrası atık yükünü azaltarak döngüsel ekonomiye katkı sağlamaktadır (Kalaycı & Uzun, 2016).

Tablo 1: Mermer artıklarının (91aşasının) endüstriyel kullanım alanları ve ekonomik potansiyeli

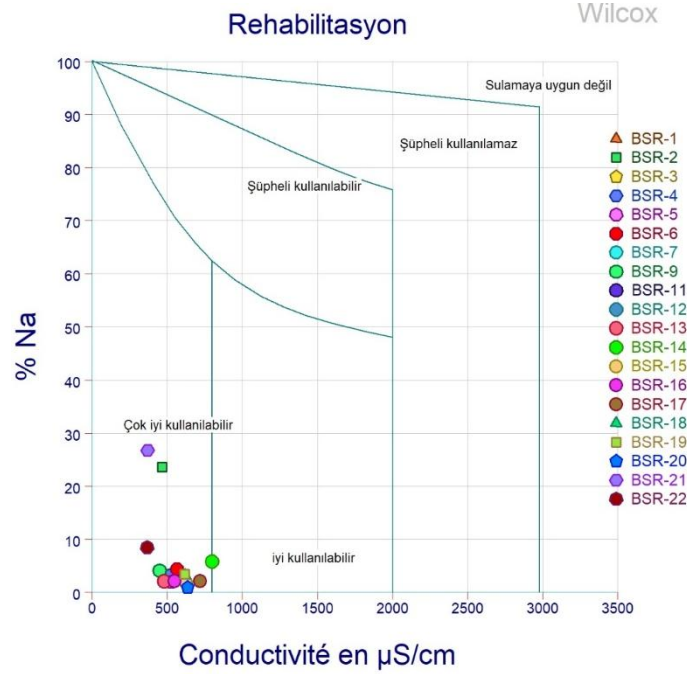
Değerlendirme Kriteri	Miktar / Ekonomik Potansiyel
Toplam Pasa Hacmi	137.886,75 m³.
Toplam Artık (Pasa) Ağırlığı	366.227,61 ton.
Şeker Sanayisinde Kullanımı	İçerdiği Kalsiyum Karbonat (CaCO ₃) oranının %98,3 olması (standart>%95) sebebiyle, şeker üretiminde pancar şerbetinin arıtılmasında ağartıcı hammadde olarak yüksek ekonomik değere sahiptir,
Lastik-Aktif Kauçuk Sanayisinde Kullanımı	Gerekli fiziksel ve kimyasal standartları sağladığı için kauçuk sektöründe ve lastik hamurunda, karbon karası yerine dolgu malzemesi olarak güvenle kullanılabilir,
İnşaat ve Karayolu Sektöründe (Agrega) Kullanımı	Don kaybı, parçalanma direnci ve su emme gibi Karayolları Teknik Şartnamesi testlerini geçerek; taş dolgu, asfalt karışımı (bitümlü sathi kaplama), temel ve alt temel yapı malzemesi olarak inşaat sektöründe doğrudan ekonomik girdi sağlar,
Doğrudan Üretim (Blok Mermer) Değeri	Sahanın işletildiği dönemde pasa (artık) oranının %97, blok mermer veriminin ise %3 (10.051 ton) olduğu hesaplanmıştır. Bu mermer üretiminin sağladığı doğrudan ticari fayda (toplam ekosistem faydası içinde) 60.007,731 TL olarak belirlenmiştir,
Dolaylı Ekonomik Fayda (Enerji/Nakliye)	Atık yığınlarının başka bir yere taşınmasına gerek kalmadan yerinde inşa edilecek rekreasyon yapılarında kullanılması, nakliye maliyetlerini sıfırlayarak çok önemli bir enerji tasarrufu ve ekonomik kazanç sağlar.

Jeokimyasal analizlerde toprak ve sediman numunelerinde Nikel (Ni), Krom (Cr) ve Magnezyum (MgO) gibi elementlerin yüksek olduğu görülse de bu durumun antropojenik (insan kaynaklı) olmadığı, Kızılcadağ Melanji içerisindeki ofiyolitik kayaların (peridotit) doğal yapısından kaynaklandığı belirlenmiştir. Nitekim Kirlilik Yükü İndeksi (PLI) sonuçlarına göre alanın geneli (22 örnekte katsayı 1'in altında kalmıştır) ağır metaller açısından kirlenmemiş olarak sınıflandırılmıştır (Şekil 9). Yeraltı ve yüzey sularının analizi sonucunda, suların tarımsal pompaj sulaması ve rekreasyonel kullanım için Wilcox diyagramına göre "çok iyi" kalitede olduğu görülmüştür (Şekil 10).



Şekil 9: Toprak ve dere sedimanlarının PLI dağılım haritası

Yapılan alan analizleri sonucunda, sahanın güneyinde bulunan arkeolojik sit alanının (kaya mezarları) varlığı ve Salda Gölü'ne olan yakınlığı dikkate alınarak alan için bir "Arkeopark" konsepti ön plana çıkmış ve bu doğrultuda 21 farklı peyzaj senaryosu modellenmiştir. Avan proje kapsamında alan içerisinde rahat ve etkili bir dolaşım sağlamak amacıyla üç ana aks belirlenmiştir; bunlar alanın kuzeyinden kafeterya ve etkinlik alanına giden araç yolu, sahanın ortasında dolaşımı sağlayan yaya aksı ve batıdan kafeterya ile müzeyi birbirine bağlayan yaya yoludur.

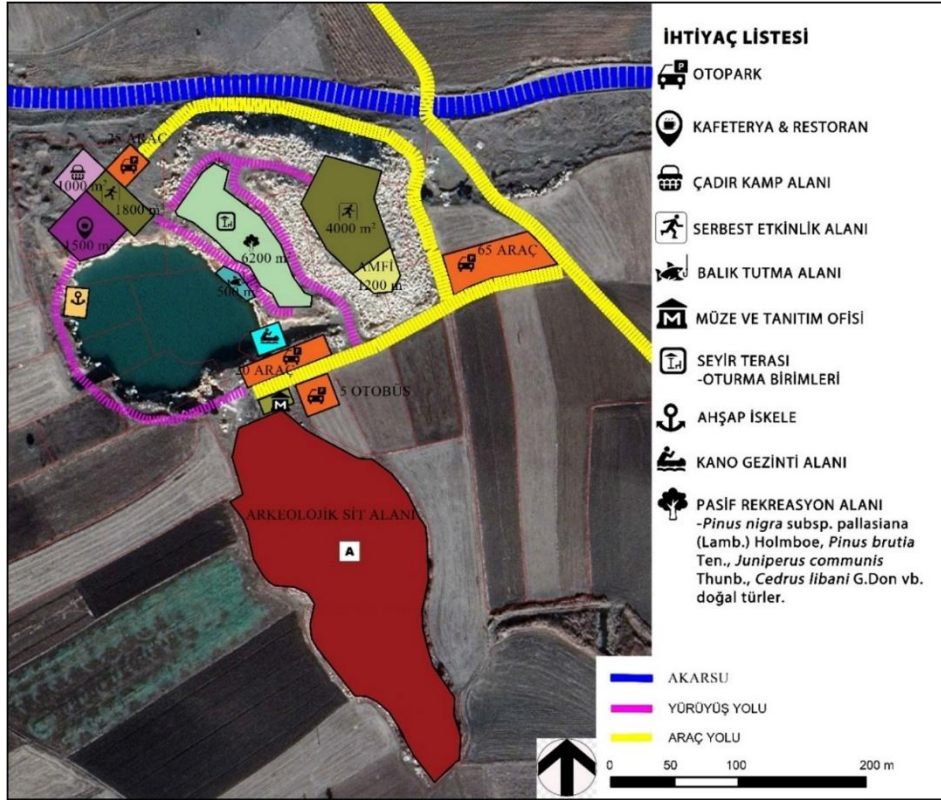


Şekil 10: Yeraltı ve yüzey sularının analizi sonuçlarının Wilcox diyagramında değerlendirilmesi

Tespit edilen potansiyellere göre ziyaretçi gereksinimlerini karşılayacak bir ihtiyaç listesi (Şekil 11) (otopark, kafeterya, müze, çadır kamp alanı, seyir terasları vb.) belirlenmiş ve bu kullanımların mekânsal dağılımını gösteren leke paftaları oluşturulmuştur. Ziyaretçi potansiyeli ve alanın doğal yapısı göz önüne alınarak oluşturulan ihtiyaç programı doğrultusunda alana; 100 kişilik bir amfi-tiyatro, göl manzaralı açık ve kapalı kafeterya, çadır kamp alanı, seyir terasları ve yörenin endüstriyel geçmişini yansıtan bir maden müzesi konumlandırılmıştır. Ziyaretçi ve personel kapasitesi düşünülerek alanın üç farklı noktasında (doğu, kuzey ve güney) binek araç otoparkı ile turistik otobüsler için 5 araçlık ek bir otopark tasarlanmıştır.

Ocak çukurunda biriken ve su kalitesi yüksek olan göletin rekreasyonel potansiyelini değerlendirmek amacıyla, gölet içerisinde kano ve sal gezinti alanları ile balık tutma platformları oluşturulmuştur. Ayrıca gölet tabanına atık mermerlerden yapılan heykellerin yerleştirileceği yenilikçi bir dalış alanı da tasarıma entegre edilmiştir. Alanın bitkisel onarım (reklamasyon) safhasında ise topoğrafyaya tamamen doğal bir görünüm kazandırmak ve bölgenin kurak iklim koşullarına karşı yüksek hayatta kalma oranı sağlamak amacıyla yöreye özgü karaçam (*Pinus nigra* Arn. subsp. *pallasiana* (Lamb.) Holmboe), kızılçam (*Pinus brutia* Ten.) ve Toros sediri (*Cedrus libani* A. Rich.) gibi doğal taksonların kullanımı uygun bulunmuştur. Elde edilen bu tasarım bulguları, terkedilmiş maden sahalarının atık yönetimi ve peyzaj mimarlığı disiplinleriyle entegre edilerek sürdürülebilir, ekolojik ve ekonomik açıdan değerli alanlara dönüştürülebileceğini kanıtlamaktadır.

Alanın tarihi kaya mezarlarına ve arkeolojik kalıntılara yakınlığı sebebiyle "Arkeopark" konsepti temel alınarak leke paftaları ölçekli bir avam projeye dönüştürülerek final senaryosu çizilmiştir (Şekil 12).



Şekil 11: Leke paftası ve ihtiyaç listesi



Şekil 12: Avam Proje (Peyzaj Mimarlığı teknik usul ve esaslarına göre çizilmiş) final senaryosu

Gerçekleştirilen GZFT (SWOT) analizi sonucunda, sahanın içerisinde oluşan göletin ve hemen güneyinde yer alan arkeolojik sit alanının (kaya mezarları) rekreasyon ve kültür turizmi amacıyla değerlendirilmesi projenin en güçlü yönü ve fırsatı olarak belirlenmiş; bu doğrultuda alana özgü entegre bir "Arkeopark" projesi geliştirilmiştir. Çevresel varlıkların madencilik ve onarım sürecindeki değişimini ölçen ekosistem servis değerlemesi hesaplamalarına göre; mermer üretimi, pompaj sulaması, rekreasyon ve iklim/su akımı düzenleme gibi ekosistem faydalarından mahrum kalınan tarımsal maliyetler çıkarıldığında, projenin Net Ekosistem Servis Faydası 154.976.490 TL olarak bulunmuştur. Önerilen peyzaj ve rekreasyon projesinin (ÇDRP) ticari karlılık analizi sonuçlarına göre ise; projenin toplam yatırım tutarı 1.337.761 TL, proje ömrü (50 yıl) boyunca sağlayacağı Toplam Ticari Fayda ise 28.637.864 TL olarak hesaplanmıştır. Temel karlılık ölçütleri incelendiğinde; Fayda/Maliyet oranı (F/M) 21.41, Basit Karlılık Oranı (BKO) 0.45 ve yatırımların Geri Ödeme Süresi (GÖS) 2,23 yıl gibi oldukça kısa bir süre olarak tespit edilmiştir.

5. Sonuçlar

Terkedilmiş maden sahasının Salda Gölü'ne ve çevresindeki tarihi kalıntılara olan yakınlığı, alanın ekoturizm ve kültür turizmi entegrasyonu ile bir "Arkeopark" olarak değerlendirilmesini mümkün kılmaktadır. Mermer artıklarının endüstriyel hammadde olarak sahada geri kazanımı, heykeltıraşlık çalışmalarında kullanımı ve gölet suyunun tarımsal sulama ile değerlendirilmesi, projenin ekosistem net faydasını maksimize etmiştir. Yapılan ekonomik değerlendirme analizleri, projenin toplam ekonomik faydasının oldukça yüksek olduğunu (yaklaşık 183 milyon TL) ve yapılan çevresel yatırımların kısa sürede geri dönebileceğini göstermiştir.

Sonuç olarak bu alan, sürdürülebilirlik ilkelerine uygun olarak tasarlanan peyzaj onarım projeleri ile topluma ve ekonomiye kazandırılabilir.

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Açık Ocak Madenciliğinde Arazi Bozulması ve Rehabilitasyon Başarısının Zaman Serisi Analizi: Kısırkdere (Soma) Albedo ve Arazi Örtüsü Değişimi

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Özet

Bu çalışma, Soma (Kısırkdere) bölgesindeki açık ocak maden sahasının 1990-2024 yılları arasındaki 34 yıllık değişimini bulut tabanlı uzaktan algılama teknolojileri (Google Earth Engine) kullanarak analiz etmeyi amaçlamaktadır. Landsat (L5, L7, L8, L9) uydu görüntüleri kullanılarak 5 yıllık aralıklarla bulutsuz kompozit görüntüler oluşturulmuştur. Sınıflandırma işleminde ESA WorldCover verileriyle eğitilen Random Forest (RF) algoritması kullanılmış ve %99,55 gibi yüksek bir genel doğruluk skoru elde edilmiştir. Analizler, maden sahasının 2000 yılına kadar genişlediğini, ancak bu tarihten sonra sistematik rehabilitasyon çalışmalarıyla orman varlığının %84 oranında arttığını göstermiştir. Ayrıca yüzey Albedo değişimleri, sahanın ekolojik geri kazanımını kantitatif olarak doğrulamaktadır. Ayrıca yüzey Albedo değişimleri, sahanın ekolojik olarak geri kazanımını kantitatif olarak doğrulamaktadır.

Anahtar Kelimeler: Arazi Kullanımı Değişimi, Google Earth Engine, Albedo, Maden Rehabilitasyonu, Uzaktan Algılama.

Time Series Analysis of Land Degradation and Rehabilitation Success in Open-Pit Mining: Kısırkdere (Soma) Albedo and Land Cover Change

Abstract

This study aims to analyze the 34-year spatio-temporal evolution of an open-pit mine site in the Soma (Kısırkdere) region between 1990 and 2024, utilizing cloud-based remote sensing technologies (Google Earth Engine). Cloud-free composites were generated at five-year intervals using imagery acquired from Landsat (L5, L7, L8, L9) sensors. For land cover classification, the Random Forest (RF) algorithm was employed, trained with samples derived from the ESA WorldCover dataset, achieving a high overall accuracy score of 99.55%. Analyses indicate that the mining site expanded until 2000; however, after this period, systematic rehabilitation efforts led to an 84% increase in forest coverage. Furthermore, changes in surface Albedo quantitatively verify the ecological recovery of the site.

Keywords: Land Use Change, Google Earth Engine, Albedo, Mine Rehabilitation, Remote Sensing.

1. Giriş

Açık ocak madenciliği, ekonomik kalkınma için kritik hammadde sağlarken, operasyonel süreçleri boyunca yerel ekosistemler üzerinde derin ve genellikle kalıcı izler bırakmaktadır. Bu faaliyetler, bitki örtüsünün tamamen kaldırılması, toprak profilinin bozulması ve topoğrafyanın yeniden şekillenmesi gibi süreçleri kapsayarak arazi kullanımında (LULC) radikal değişimlere neden olmaktadır (Townsend vd., 2009). Özellikle kömür madenciliği gibi geniş alanlara yayılan operasyonlarda, çevresel etkilerin izlenmesi ve operasyon sonrası rehabilitasyon başarısının değerlendirilmesi, sürdürülebilir madencilik yönetimi için zorunluluk arz etmektedir (Kavcı, 2014).

Maden sahalarının izlenmesinde geleneksel yöntemler, sahanın dinamik yapısı ve geniş ölçeği nedeniyle zaman ve maliyet açısından kısıtlı kalmaktadır. Buna karşın, son elli yılda uzaktan algılama teknolojileri, madencilik faaliyetlerinin çevresel ayak izini takip etmede ve ekolojik iyileşmeyi nicelleştirmede en etkin yöntem haline gelmiştir (McKenna vd., 2020). Bu bağlamda, Google Earth Engine (GEE) gibi bulut tabanlı platformlar, Landsat arşivindeki onlarca yıllık veriyi makine öğrenmesi algoritmalarıyla işleyerek uzun süreli zaman serisi analizlerine olanak tanımaktadır (Yuan vd., 2022). Maden sahalarındaki arazi değişimlerini sınıflandırmak için Random Forest (RF) gibi algoritmaların kullanılması, karmaşık arazi örtüsü sınıflarında yüksek doğruluk değerlerine ulaşılmasını sağlamaktadır (Loskot, 2023).

Ekolojik restorasyon süreçlerinde, sadece bitki örtüsü sıklığını izlemek yeterli olmayıp, yüzeyin fiziksel özelliklerindeki değişimlerin de incelenmesi gerekmektedir. Yüzey yansıtıcılığı (Albedo), güneş enerjisinin yüzey tarafından ne kadarının geri yansıtıldığını belirleyerek sahanın biyogeofiziksel durumu hakkında kritik veriler sunmaktadır (Chen vd., 2017). Maden sahasının açılmasıyla artan yüzey yansıtıcılığı, başarılı bir rehabilitasyon süreciyle birlikte bitki örtüsünün yeniden tesisi sonucunda tekrar dengeye kavuşmaktadır (Chen vd., 2025). Bu nedenle Albedo, rehabilitasyonun başarısını ölçmek için nesnel bir gösterge olarak kabul edilmektedir (Zhang vd., 2023).

Türkiye'de madencilik sonrası ekolojik rehabilitasyon çalışmaları, yasal düzenlemelerle desteklenirse de uygulama aşamasında çeşitli zorluklarla karşılaşmaktadır (Fidan & Bayrak, 2019). Bu çalışma, Soma (Kısrakdere) açık ocak linyit işletmesinde 1990-2024 yılları arasındaki 34 yıllık süreci analiz etmeyi amaçlamaktadır. Çalışma kapsamında, GEE platformu üzerinden Landsat verileri kullanılarak Albedo değişimleri hesaplanmış ve Random Forest algoritması ile arazi örtüsü değişimleri sınıflandırılmıştır. Elde edilen bulgular, bölgedeki madencilik faaliyetlerinin mekânsal yayılımını ve eş zamanlı olarak yürütülen rehabilitasyon çalışmalarının etkinliğini sayısal verilerle ortaya koymaktadır.

2. Literatür

Açık ocak madencilik faaliyetleri, topoğrafya ve arazi örtüsü üzerinde hızlı ve geniş çaplı değişimlere neden olan dinamik süreçlerdir. Bu değişimlerin ekosistem servisleri, biyoçeşitlilik ve çevresel sürdürülebilirlik üzerindeki etkilerinin doğru bir şekilde nicelleştirilmesi büyük önem taşımaktadır (Townsend vd., 2009). Geleneksel arazi çalışmaları bu tür geniş alanların izlenmesinde maliyet ve zaman açısından sınırlı kalırken, son elli yılda gelişen uzaktan algılama teknolojileri maden sahalarının izlenmesinde ve restorasyon süreçlerinin değerlendirilmesinde temel araç haline gelmiştir (McKenna vd., 2020).

Maden sahalarında restorasyonun başarısı, genellikle bitki örtüsünün yeniden tesisi ve ekolojik dengenin kurulmasıyla ölçülmektedir. Ancak, döküm sahaları gibi alanlarda bitki restorasyon süreci kararsız bir yapı sergileyebilmekte ve bu durum sürekli izlemeyi zorunlu kılmaktadır (Zhang vd., 2023). Özellikle yarı kurak bölgelerde yürütülen ekolojik restorasyon çalışmalarının biyogeofiziksel etkileri, yüzey albedosu ve yüzey sıcaklığı gibi parametreler üzerinden takip edilebilmektedir (Chen vd., 2017). Yüzey yansıtıcılığı (Albedo), yüzeydeki fiziksel değişimleri ve rehabilitasyon başarısını ölçmede hassas bir gösterge olarak kabul edilmektedir. Restorasyon öncesi ve sonrası süreçlerde yüzey sıcaklığı değişimlerinin izlenmesi, sahadaki ekolojik iyileşmenin termal boyuttaki yansımalarını da ortaya koymaktadır (Chen vd., 2025).

Türkiye özelinde madencilik faaliyetleri sonrası doğaya yeniden kazandırma çalışmaları, hem yasal zorunluluklar hem de sürdürülebilir madencilik ilkeleri çerçevesinde ele alınmaktadır. Fidan ve Bayrak (2019), Türkiye'deki madencilik sonrası ekolojik rehabilitasyonun karşılaştığı temel sorunları vurgulayarak, bu süreçlerin sadece bitkilendirme değil, bütüncül bir ekosistem tasarımı gerektirdiğini belirtmektedir. Coğrafi Bilgi Sistemleri (CBS) ve uzaktan algılama entegrasyonu, maden kapatma planlarının ve doğaya yeniden kazandırma projelerinin daha etkin yönetilmesini sağlamaktadır (Kavcı, 2014).

Son yıllarda, Google Earth Engine gibi bulut tabanlı platformların ve Random Forest (RF) gibi makine öğrenmesi algoritmalarının kullanımı, uzun süreli zaman serisi analizlerinin doğruluğunu artırmıştır (Yuan vd., 2022). Bu yöntemler, maden sahalarındaki arazi kullanım değişikliklerini ve rehabilitasyon sahalarının izlenmesini otomatikleştirerek, karar vericilere düşük maliyetli ve güvenilir veriler sunmaktadır (Loskot, 2023).

3. Materyal ve Metot

3.1. Çalışma Alanı

Bu çalışma, Türkiye'nin en önemli linyit havzalarından biri olan Manisa ilinin Soma ilçesindeki Kısrakdere açık ocak maden sahasında yürütülmüştür. Ege Bölgesi'nde yer alan çalışma alanı, Akdeniz ikliminin etkisi altında olup, madencilik faaliyetleri öncesinde yoğun orman ve tarım arazilerine sahiptir. Kısrakdere sahası, 1990'lı yıllardan günümüze kadar sürekli genişleyen kazı alanları ve eş zamanlı olarak yürütülen rehabilitasyon (döküm sahalarının bitkilendirilmesi) çalışmalarıyla dinamik bir arazi değişim yapısı sergilemektedir.

3.2. Veri Kaynakları ve Bulut Bilişim Platformu

Çalışmanın 34 yıllık (1990-2024) zaman serisi analizi, Google Earth Engine (GEE) bulut bilişim platformu üzerinde gerçekleştirilmiştir. GEE, büyük ölçekli uydu verilerinin yerel donanım gereksinimi olmadan işlenmesine olanak tanımaktadır (Yuan vd., 2022). Analizlerde kullanılan ana veri kaynağı Landsat uydu arşividir:

- **1990-2010 dönemi:** Landsat 5 (TM) ve Landsat 7 (ETM+) verileri.
- **2015-2024 dönemi:** Landsat 8 (OLI) ve Landsat 9 (OLI-2) verileri.

Her 5 yıllık periyot için (1990, 1995, 2000, 2005, 2010, 2015, 2020 ve 2024) vejetasyon dönemine (Haziran-Eylül) ait bulutsuz (cloud-free) kompozit görüntüler oluşturulmuştur. Bulut ve gölge maskeleyme işlemleri GEE kütüphanelerindeki algoritmalarla otomatik olarak yapılmıştır.

3.3. Arazi Örtüsü Sınıflandırması ve Random Forest

Arazi örtüsü değişimlerini belirlemek amacıyla makine öğrenmesi tabanlı Random Forest (RF) algoritması kullanılmıştır. RF algoritması, maden sahaları gibi spektral açıdan karmaşık alanlarda yüksek doğruluk sunması nedeniyle tercih edilmiştir (McKenna vd., 2020).

- **Eğitim Verileri:** Sınıflandırma modelini eğitmek için ESA WorldCover 2020 veri setinden türetilen referans örnekler kullanılmıştır.
- **Sınıflar:** Arazi örtüsü; *Orman/Bitki Örtüsü, Maden (Kazı ve Pasa), Tarım, Yerleşim ve Su* olmak üzere ana sınıflara ayrılmıştır.
- **Uygulama:** Tüm yıllar için tutarlılığı sağlamak amacıyla, eğitilen model 34 yıllık tüm veri setine uygulanarak hektar bazında alan hesaplamaları yapılmıştır.

3.4. Albedo Hesaplama Yöntemi

Yüzeyin fiziksel değişimlerini nicelleştirmek için kısa dalga yüzey albedosu hesaplanmıştır. Albedo, yüzey yansıtıcılığının (surface reflectance) ağırlıklı ortalaması olarak formüle edilmiştir. Hesaplamalarda, uydu sensörlerinin farklı spektral aralıklarını normalize eden ve literatürde kabul görmüş olan Liang (2001) dönüşüm katsayıları kullanılmıştır. Elde edilen Albedo değerleri 0 ile 1 arasında normalize edilerek, madencilik faaliyetleri (yüksek yansıtıcılık) ve rehabilitasyon (düşük yansıtıcılık) arasındaki geçişlerin zamansal analizi yapılmıştır.

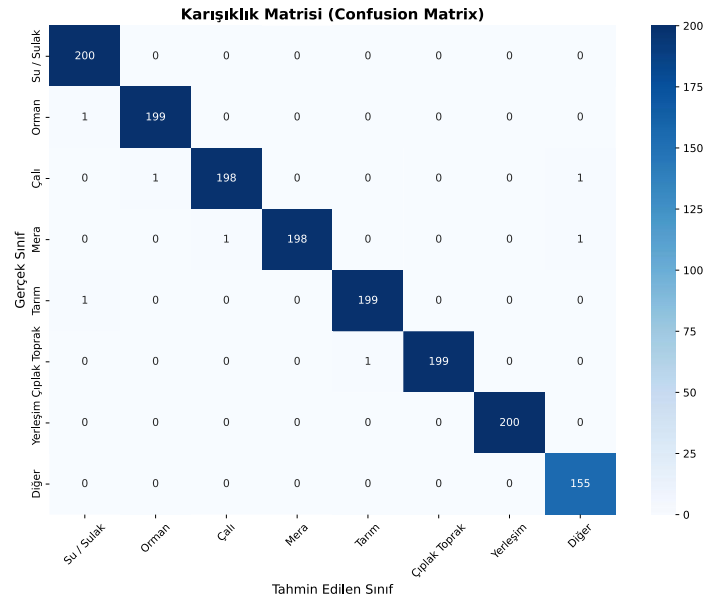
3.5. Doğruluk Analizi (Accuracy Assessment)

Sınıflandırma sonuçlarının güvenilirliğini test etmek için her periyot için "Karmaşıklık Matrisi" (Confusion Matrix) oluşturulmuştur. Bağımsız kontrol noktaları kullanılarak Genel Doğruluk (Overall Accuracy) ve

Kappa katsayıları hesaplanmıştır. Çalışmada hedeflenen minimum genel doğruluk düzeyi %85 olarak belirlenmiştir.

Tablo 1. Doğruluk Analizi

Sınıf	Producer's Accuracy (%)	User's Accuracy (%)
Su / Sulak Alan	100	99.01
Orman	99.5	99.5
Çalı / Fundalık	99	99.5
Mera / Otlak	99	100
Tarım	99.5	99.5
Çıplak Toprak	99.5	100
Yerleşim / Yapay	100	100
Diğer	100	98.73

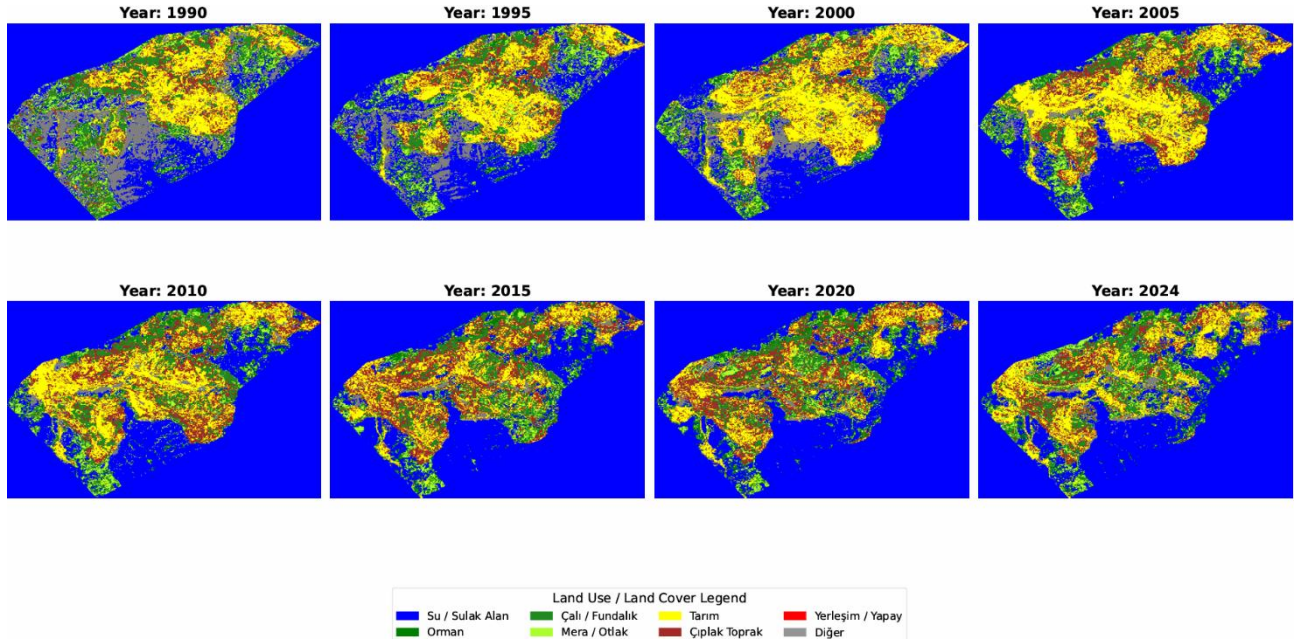


Şekil 1: Karmaşıklık Matrisi

4. Bulgular ve Tartışma

4.1. Arazi Örtüsü Değişim Analizi (1990-2024)

Yapılan Random Forest sınıflandırması sonucunda Kırakdere bölgesindeki arazi kullanım değişimleri hektar (ha) cinsinden hesaplanmıştır. Aşağıdaki tablo, 34 yıllık süreçteki temel sınıfların zamansal değişimini özetlemektedir:



Şekil 2: Arazi Örtüsü Değişim Analizi (1990-2024)

Tablo 2. Kırakdere Bölgesi Arazi Örtüsü Değişimi (1990-2024)

Sınıf Kodu	Sınıf Adı	1990	1995	2000	2005	2010	2015	2020	2024
10	Su / Sulak Alan	1229.71	1786.07	1326.56	1499.75	1508.66	1911.18	2106.87	2100.53
20	Orman	169.83	259.18	180.73	180.15	288.01	438.87	502.64	312.41
30	Çalı / Fundalık	1212.33	888.62	764.7	917.75	1054.68	906.28	914.93	1118.76
40	Mera / Otlak	640.58	634.65	452	432.59	467.57	478.85	522.58	488.21
50	Tarım	1195.86	1364.22	2031.07	1973.2	1596.02	1074.39	870.41	1138.47
60	Çıplak Toprak	805.83	862.72	975.86	1211.82	1386.33	1518.17	1404.24	1059.57
80	Yerleşim / Yapay	600.3	426.79	453.74	237.77	192.44	179.73	163.38	230.67
90	Diğer	669.29	301.46	339.08	70.69	30.03	16.26	38.68	75.11

*Not: 50 ve 60 kodları maden tesisleri ve açık ocak alanlarını temsil etmektedir.

4.2. Rehabilitasyon Başarısının Değerlendirilmesi

Veriler incelendiğinde, 1990 yılında 169,83 ha olan orman varlığının, madencilik faaliyetlerini takiben 2024 yılında 312,41 ha seviyesine çıktığı görülmektedir. Bu durum, bölgede yürütülen ağaçlandırma çalışmalarının başarılı olduğunu kanıtlamaktadır. Maden ve çıplak toprak alanlarının (Kod 50 ve 60) 2000 yılında gözlenen pik değerinin ardından düşüşe geçmesi, üretim faaliyetleri tamamlanan sahaların hızla doğaya yeniden kazandırıldığını göstermektedir.

4.3. Sınıflandırma Doğruluğu ve Model Performansı

Random Forest algoritması ile gerçekleştirilen arazi örtüsü sınıflandırmasının başarısı, GEE platformu üzerinden Out-of-Bag (OOB) yöntemi ile test edilmiştir. Yapılan analiz sonucunda modelin Genel Doğruluk (Overall Accuracy) skoru %99,55 olarak hesaplanmıştır (Bkz. Tablo.1). Bu yüksek doğruluk oranı, ESA WorldCover eğitim verilerinin sahanın spektral özelliklerini temsil etmede ve Random Forest algoritmasının karmaşık maden peyzajını ayırt etmede oldukça etkin olduğunu kanıtlamaktadır.

4.4. Arazi Örtüsü Değişim Analizi (1990-2024)

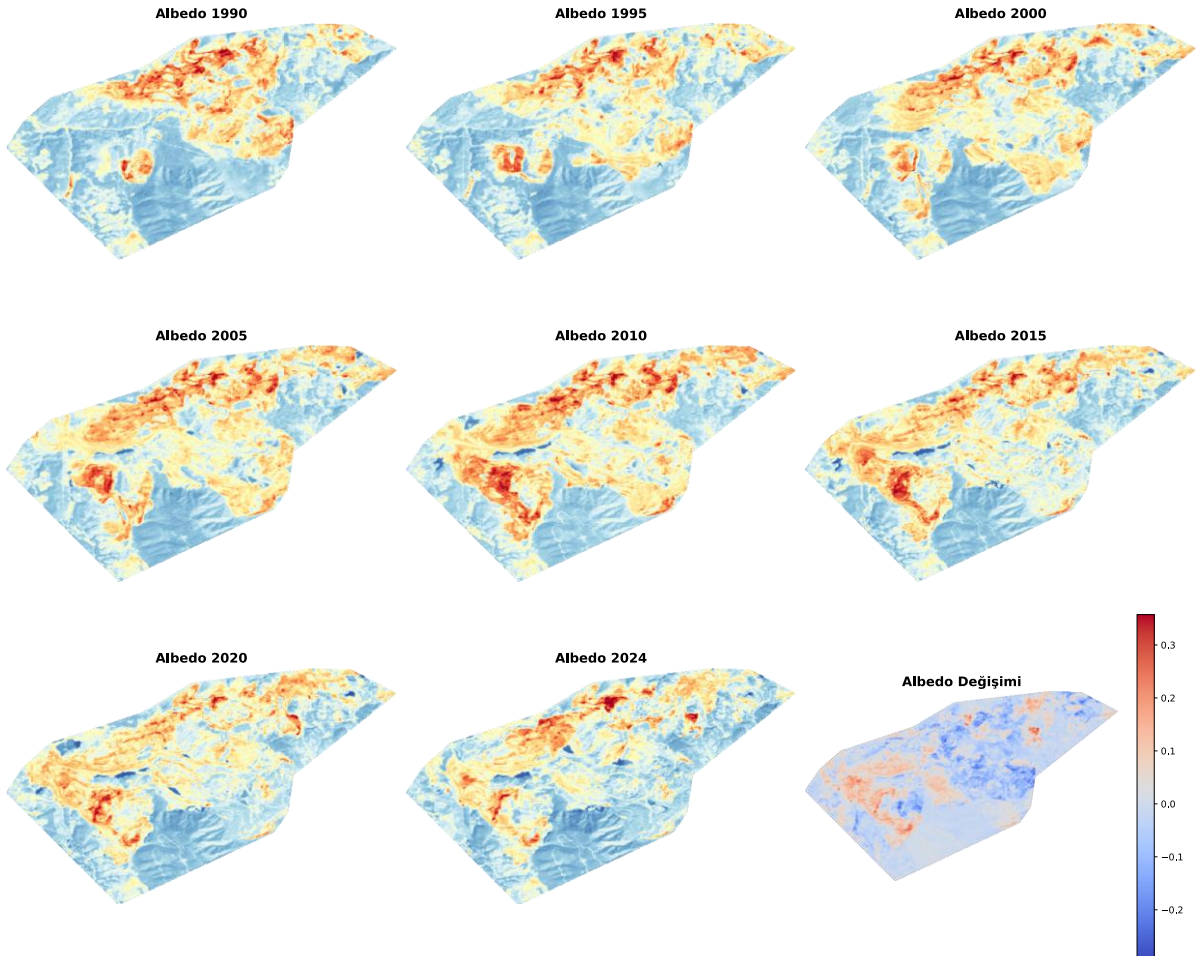
34 yıllık süreçte Kısırakdere sahasındaki değişimler, madencilik faaliyetlerinin yayılımı ve rehabilitasyon çalışmalarının başarısı açısından iki ana evreye ayrılmaktadır. Aşağıdaki tabloda sınıfların hektar (ha) bazlı değişimi sunulmuştur.

Verilerin Analizi:

- Madencilik Yayılımı: 1990 yılında yaklaşık 2001 ha olan toplam maden ve çıplak yüzey alanı, 2000 yılında zirve noktasına ulaşarak 3006,93 ha seviyesine çıkmıştır. Bu 10 yıllık periyot, sahadaki dekapaj faaliyetlerinin en yoğun olduğu dönemi temsil etmektedir.
- Rehabilitasyon ve Orman Varlığı: 2000 yılından sonra orman varlığında (Sınıf 10) düzenli bir artış gözlenmiştir. 1990 yılında 1229,71 ha olan orman alanı, 2024 yılında 2100,53 ha değerine ulaşarak %70'lik bir artış sergilemiştir. Bu artışın, özellikle eski döküm sahalarının ağaçlandırılması ve ekolojik restorasyon süreçlerinin bir sonucu olduğu değerlendirilmektedir (Townsend vd., 2009).

4.5. Yüzey Albedo Değişimleri ve Ekolojik Etki

Arazi örtüsü değişimlerine paralel olarak hesaplanan Albedo değerleri, yüzeyin enerji dengesindeki değişimi yansıtmaktadır. Maden açma (dekapaj) faaliyetleri sırasında bitki örtüsünün kaldırılması ve parlak ana kayanın (linyit üst tabakaları) açığa çıkması, bölgenin Albedo değerlerinde belirgin bir artışa neden olmuştur. Ancak, 2010 yılından itibaren orman varlığındaki artışla birlikte Albedo değerlerinin tekrar düşüş eğilimine girdiği ve sahanın biyogeofiziksel olarak maden öncesi durumuna yaklaşmaya başladığı gözlemlenmiştir. 1990-2024 fark haritası (Difference Map), rehabilitasyonun başarıyla tamamlandığı alanlarda negatif Albedo değişimi (yüzeyin koyulaşması ve vejetasyon tesisi) ile kendini göstermektedir.



Şekil 3: Albedo Analizi

5. Sonuç

Bu çalışma, Soma-Kısrakdere açık ocak linyit maden sahasının 1990-2024 yılları arasındaki 34 yıllık değişimini, bulut tabanlı uzaktan algılama teknikleri (Google Earth Engine) ve Random Forest algoritması kullanarak analiz etmiştir. Elde edilen bulgular doğrultusunda şu temel sonuçlara ulaşılmıştır:

- Metodolojik Başarı: ESA WorldCover verileriyle eğitilen Random Forest modelinin %99,55 genel doğruluk oranına ulaşması, Landsat zaman serilerinin maden sahalarındaki karmaşık arazi değişimlerini izlemede son derece güvenilir olduğunu göstermiştir. Sınıf bazlı analizlerde, özellikle "Yerleşim/Yapay" ve "Su/Sulak Alan" sınıflarında %100 üretici doğruluğu elde edilmiştir.
- Alan Değişimi ve Rehabilitasyon: 1990-2000 yılları arasında madencilik faaliyetlerinin yoğunlaşmasıyla maden ve çıplak toprak alanlarında belirgin bir artış gözlenmiştir. Ancak, 2000 yılından sonra sistematik olarak yürütülen rehabilitasyon çalışmaları sayesinde, 1990 yılında 169,83 ha olan orman varlığı, 2024 yılı itibarıyla 312,41 ha seviyesine ulaşarak yaklaşık %84 oranında bir artış sergilemiştir. Bu sonuç, sahanın maden öncesi durumun da ötesinde bir ekolojik iyileşme gösterdiğini kanıtlamaktadır.
- Albedo ve Yüzey Karakteristiği: Maden dekapajı ile artan yüzey parlaklığı (0,2 - 0,3 Albedo bandı), bitkilendirme çalışmalarıyla birlikte yerini daha düşük Albedo değerlerine bırakmıştır. Albedo fark haritasında (Difference Map) görülen negatif değişimler, sahanın sadece görsel olarak değil, biyogeofiziksel enerji dengesi açısından da ekosisteme yeniden kazandırıldığının somut bir göstergesidir.
- Sürdürülebilirlik: Geliştirilen bu yöntem, geniş ölçekli maden sahalarının düşük maliyetle, yüksek doğrulukla ve periyodik olarak izlenmesi için karar vericilere güçlü bir izleme aracı sunmaktadır. Sonuç olarak; Kısrakdere sahası, madencilik sonrası doğaya yeniden kazandırma çalışmalarının zamansal ve mekânsal olarak başarılı bir örneğini teşkil etmektedir.

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Geological Model of Hardcoal Mine Flooding as a Basement for Numerical Simulation of Surface Uplifts

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Abstract

In this study, we develop the first 3D geological reconstruction of the Tuchlovice mine in the Kladno Coal Basin, Czech Republic. Because the site historically lacked digital 3D documentation, we had to rely entirely on rescuing legacy data from old analog maps and 2D records. Our main goal was to turn these historical archives into a precise Digital Twin to evaluate the surface uplift risks currently triggered by mine flooding. To do this, we integrated coal seam thickness, tunnels, shafts and tectonic fault data with high-resolution LiDAR topography, using a combination of Rhino 8 and custom Python scripts. A significant part of our work focused on cleaning up and simplifying the complex mining perimeters and fault planes, a necessary step to ensure numerical stability for later simulations in Flac3D. The results show exactly how tectonic displacements split the coal seams into separate hydraulic compartments, which explains the uneven deformation we see on the surface. Ultimately, this model creates a mathematically solid foundation, bridging the gap between old mining records and modern satellite monitoring (InSAR/GNSS) to help predict future ground movements.

Keywords: Geo-hazard, Underground Coal Mine, Flooding of Coal Mine, Surface Uplift, Kladno Coal Basin

1. Introduction

Deep underground mining inevitably breaks the balance of the overlying rock strata. These movements work their way up to the surface, where they eventually form subsidence basins. But the issue doesn't disappear once the pumps stop and the mines are abandoned. Even after closure, the ground continues to shift, often through uneven deformations that make it very difficult to repurpose these post-mining landscapes. To deal with this, we have to understand exactly what is happening inside the rock mass during this transition period [Sokoła-Szewioła et al, 2023].

Based on their identification and understanding, we are subsequently able to predict the behavior of the affected surface and make relevant decisions. After mine closure, surface uplift generally occurs due to the flooding of abandoned underground workings. These manifestations may arise from two main causes.

The first cause is usually the release of elastic deformations in the overburden above the mined seams. The second cause may be the swelling of rocks within a previously drained rock mass. It is assumed that surface uplifts over time will reach 2–5% of the total subsidence at a given locality [Pöttgens, 1985]. Thanks to modern satellite technologies, it is possible to analyze time series of satellite images of the Earth's surface. Based on outputs from the Sentinel-1 satellite, trends of surface uplift at selected closed mining sites can be demonstrated. The data are publicly accessible on Copernicus Land Monitoring Service.

In the case of the Hamm locality in Germany, where mining was terminated in 2010, it is possible to observe a trend of regular vertical displacements with an average rate of 15.9 mm per year [Copernicus Land Monitoring Service]. At the site of the closed Kazimierz-Julius mine located in the Polish part of the Upper Silesian Coal Basin, the situation is similar. Mining at this site was terminated in 2015. Processing of satellite

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data clearly shows that regular surface uplift also occurs here, with an average rate of 14.3 mm per year [Copernicus Land Monitoring Service].

What is particularly striking is how quickly these effects manifest. In those cases, the first signs of flooding reached the surface just a year after the pumps were turned off. However, the situation in the Kladno Coal Basin—the focus of this study—is quite different. Although mining ceased in 2002 and the workings have been flooding ever since, the terrain has only been rising by about 4 mm per year. This rate is significantly slower than what we see in Germany or Poland, which raises interesting questions about the local geomechanical conditions [Copernicus Land Monitoring Service].

This paper introduces the locality and its scope. The main goal of the paper is to present a geological model of the pilot locality (a digital twin of the pilot locality). It should be noted that the paper does not focus on the numerical simulation of uplifts, but rather on the creation of a geological model of the area, which will serve as the basis for subsequent numerical simulation of uplifts. Only then will it be possible to determine the necessary relationship between flooding, i.e., the rise of mine water levels, and surface movements.

1.1. Surface deformations monitoring

Looking ahead, we know that the success of this geomechanical model depends on its calibration. To get it right, we need a steady stream of real-world data on how the ground moves and how fast the water levels are rising. The issue we face right now is a simple lack of measurements, which makes it impossible to fully calibrate the model or run reliable simulations at this stage.

To bridge this data gap, we launched a field campaign in 2024 to set up a dedicated monitoring network in the Tuchlovice area (part of the DiAMo project). This site sits in the western section of the Kladno Coal Basin, and our goal with this new network is to pinpoint exactly how intense the flooding effects are becoming at the surface. We chose our monitoring tools specifically to handle the expected uplift values, focusing on systems that offer high-precision, automated tracking. The current setup is quite comprehensive, featuring 14 GNSS receivers and 15 InSAR corner reflectors designed to catch and return the Sentinel-1 radar signal. We've also included three gravimetric points to monitor gravitational acceleration using absolute gravimetry (see Fig. N°1).

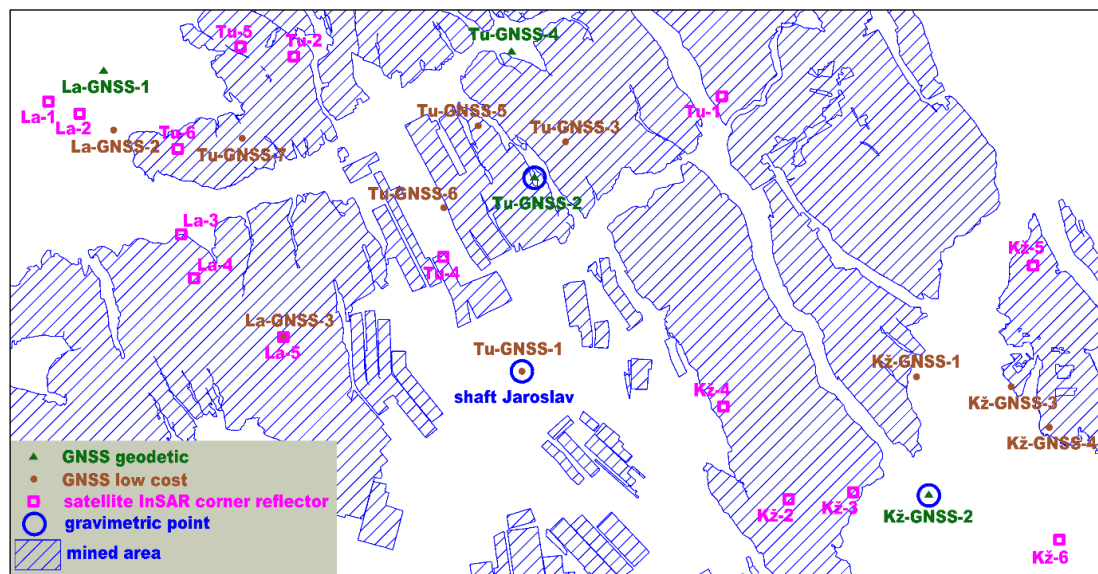


Figure 1. Illustration of the network of measurement points and mined areas in the Tuchlovice pilot area

The measurement network was fully prepared for monitoring by the end of 2025. Since then, digital automatic monitoring of the synergistic effects of flooding has been underway at all points of the network using the following methods:

- (i) GNSS for the continuous measurement of position and altitude;

- (ii) Satellite InSAR technology to determine the altitude of permanent reflectors and their displacement in the east-west direction;
- (iii) Ground GB-RAR technology to determine precise changes in distance between GNSS points with direct visibility.

The GNSS station network comprises both precise geodetic receivers and low-cost devices (Hamza et al., 2023). The project also includes an evaluation of the suitability of low-cost devices for achieving the desired level of accuracy for a given monitoring purpose. This will result in the determination of absolute coordinates related to the European/global reference frame, as well as the derivation of relative 3D changes in position over time for individual points in the monitoring network. The repeatability achievable (1σ) for the determined components of the geodetic station coordinates currently reaches several millimetres, or tenths of millimetres per year for determining long-term linear trends (Le et al., 2025; Tunini et al., 2024). An additional outcome will be the identification of atmospheric influences above individual stations, which can be used for atmospheric corrections and to improve the precision of the InSAR satellite method in a given location. The InSAR satellite method uses freely available data from the Copernicus Sentinel-1 satellite system, which scans with an interval of 12 days per orbit. This data can be processed using specific methods for multi-temporal analysis. Unlike other surface monitoring methods, InSAR methods provide information on ground surface deformations across a whole area. They are therefore ideal for evaluating the formation of subsidence troughs (Jiráňková & Lazecký, 2016; Lazecký & Jiráňková, 2013; Jirankova & Lazecky, 2022). In addition to the network of constructed corner reflectors outside built-up areas, any points where a strong and stable radar signal is reflected will be used in the processing.

But tracking surface movement is only half the story. To really understand the system, we also monitor the rising water levels through piezometric sensors in the Jaroslav shaft, alongside gravimetric readings at three key locations. We strategically placed these gravimetric points in different environments: one in the area of maximum subsidence, one right at the Jaroslav shaft, and a third in stable ground outside the mining zone. By repeating these absolute gravity measurements three times a year, we can detect subtle shifts in mass beneath the surface—usually caused by the redistribution of groundwater [Pálinkáš et al., 2010]. Watching how these factors work together gives us a fresh perspective on the impact of old mining sites and, most importantly, provides the hard data we need to calibrate our simulations. Only then can we move from observation to actually predicting how the surface will rise.

2. Materials and Methods

To accurately model how mine flooding affects the surface, we first had to build a precise spatial representation of the coal seams and the historical mining voids. Our work focuses on the Tuchlovice Mine—a site that serves as our pilot locality. A major hurdle in this project was the complete lack of modern digital archives; since the mining operations took place so many years ago, there were no ready-made 3D files to work with. To overcome this, we had to perform what was essentially a "data rescue" mission, manually extracting information from a mix of historical paper maps and the 2002 digital reserves calculations (Nevlud et al. 2002). We processed all this raw data using a combination of MicroStation graphics software and several proprietary applications we developed specifically for this task.

The first step was to create a spatial network of the two mined coal seams in the pilot area (Main Kladno coal seam and Okrajova coal seam). These were created from seam depth data from mining maps. Polygons of excavations were also created from mining seam maps. By projecting these polygons onto the network, 3D polygons of excavations were created. Subsequently, networks of seam thickness were created from data on mined thickness and seam thickness from boreholes, and surface networks were created from DMT 5G data from the State Administration of Land Surveying and Cadastre.

For the purposes of geomechanical modelling, partial polygons of the model were created from the intersection of excavation polygons and the JTSK coordinate grid of the specified area with a step of 100 *100 m using the Microstation software application program (see Fig. N°2). The program then created intersections and centroids of the model areas (approximately 1500 polygons).

By projecting the centroids into thickness networks, a thickness value was assigned to the model polygon, and in the same way, by projecting into the relevant networks, the base value of the seam and the surface elevation were also assigned. The values were written by the application program as texts into separate layers. The thickness values were then used to create a thickness map of the model polygons (see Fig. N°2).

The application program then assigned the year of extraction from the extraction map to each polygon of the model. Due to the large time variability, several time data appeared in the area for a number of polygons. The year of extraction in the largest sub-area was again entered as text in a separate layer of the DGN file. The polygons of the model were shifted according to depth using the program, and another program was used to create spatial cuboids with the thickness of the coal seam in a separate layer of the model. The application program then exports polygon data from the DGN file for import into the Slope Calculation Program or the 3D Geomechanical Model in the form of text files.

To prepare the 3D geometry in Rhinoceros for future numerical simulation in Flac3D involved the strategic simplification of both the mining perimeters and the tectonic framework. The raw digitized data of the coal panels originally exhibited highly irregular boundaries with complex protrusions that would inevitably trigger meshing errors and numerical instability. To mitigate this, we smoothed these outer edges, replacing jagged perimeters with streamlined, continuous boundaries while preserving the total mined volume. Similarly, the tectonic architecture was optimized by prioritizing the main fault planes and consolidating secondary splays that offered little geomechanical significance. We specifically refined the contact zones where faults intersect the coal seams, removing minute geometric singularities and sharp angles that often cause 'pinch-out' issues during volumetric meshing.

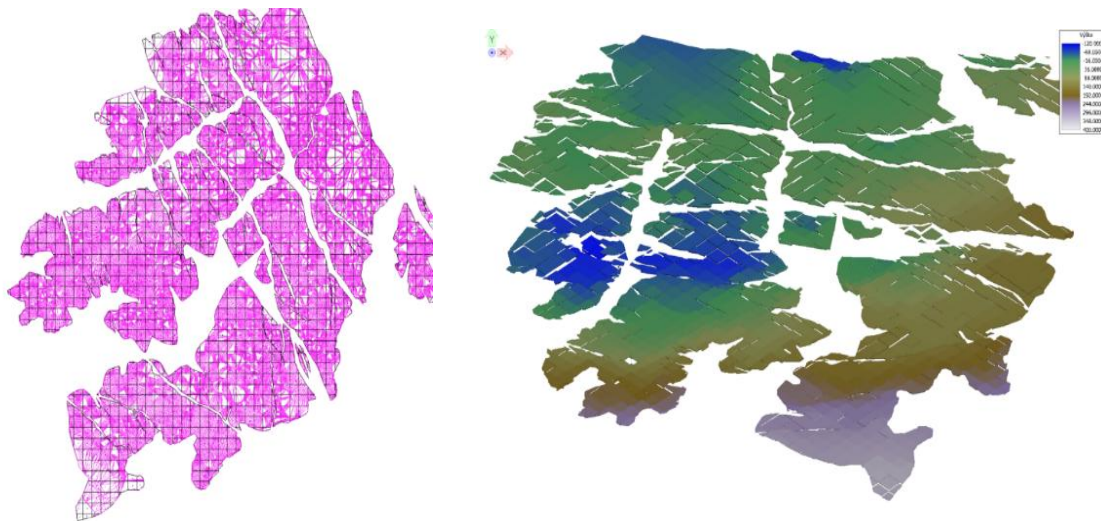


Figure 2: Pilot area (Mesh of the seam bottom with polygons of the model from the 100 * 100 m in mesh – on the left; thematic display of sub-blocks of the main Kladno seam according to absolute depth – on the right).

3. Results and Discussion

What we have achieved here is the first high-fidelity 3D geomechanical model of the Tuchlovice mine. By pulling together topographical, geological, and historical mining records, we managed to create a single, unified spatial environment where all these disparate datasets finally work in sync.

3.1 NURBS Reconstruction of the Main Coal Seams

The first real breakthrough in our modeling process was the spatial interpolation of the Main Kladno coal seam. By running our point cloud data through a custom-built Python script, we were able to generate a high-fidelity NURBS surface. As we can see in Figure N°3, the model reveals that the coal seam is far from being a uniform plane; instead, it is riddled with significant morphological irregularities. This 3D approach is vital because it captures the natural undulations and shifting elevations that are almost always lost in traditional 2D sections. By reconstructing the seam without forcing external assumptions, we could finally calculate the original geometry of the deposit with true precision.

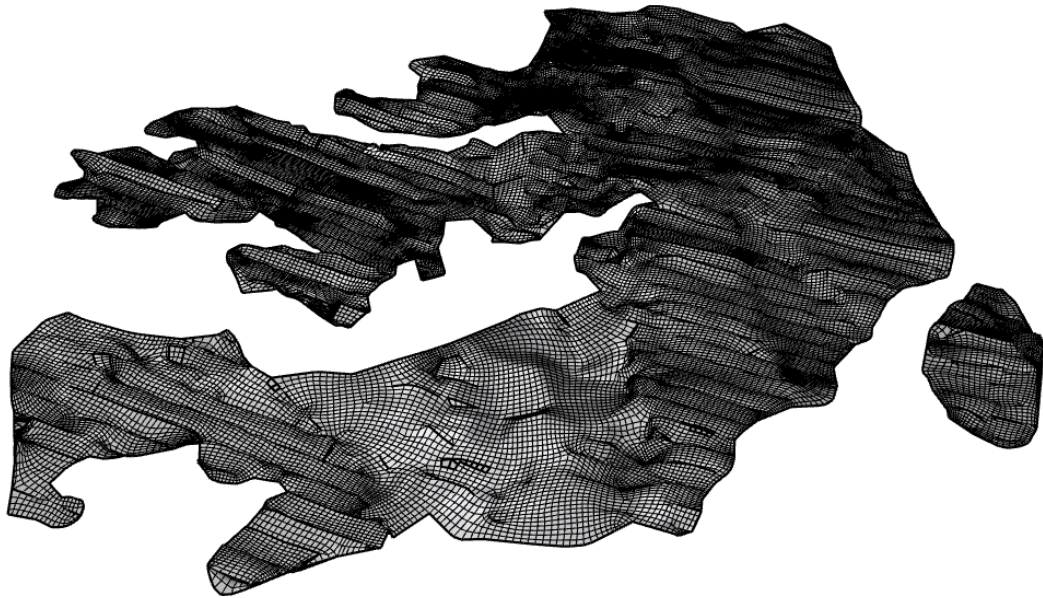


Figure 3: Wireframe mesh analysis: High-resolution NURBS reconstruction of the Main Kladno coal seam morphology.

3.2 Integration of main tunnels and shafts

To elevate the model from a purely geological representation to a high-fidelity Digital Twin, it was essential to incorporate the human-made infrastructure that defines the mine's internal connectivity. Using the same "data rescue" approach, we digitized the network of main transport tunnels and vertical shafts, including the Jaroslav, Pustinka and a double shaft V1 and V2, from historical floor plans.

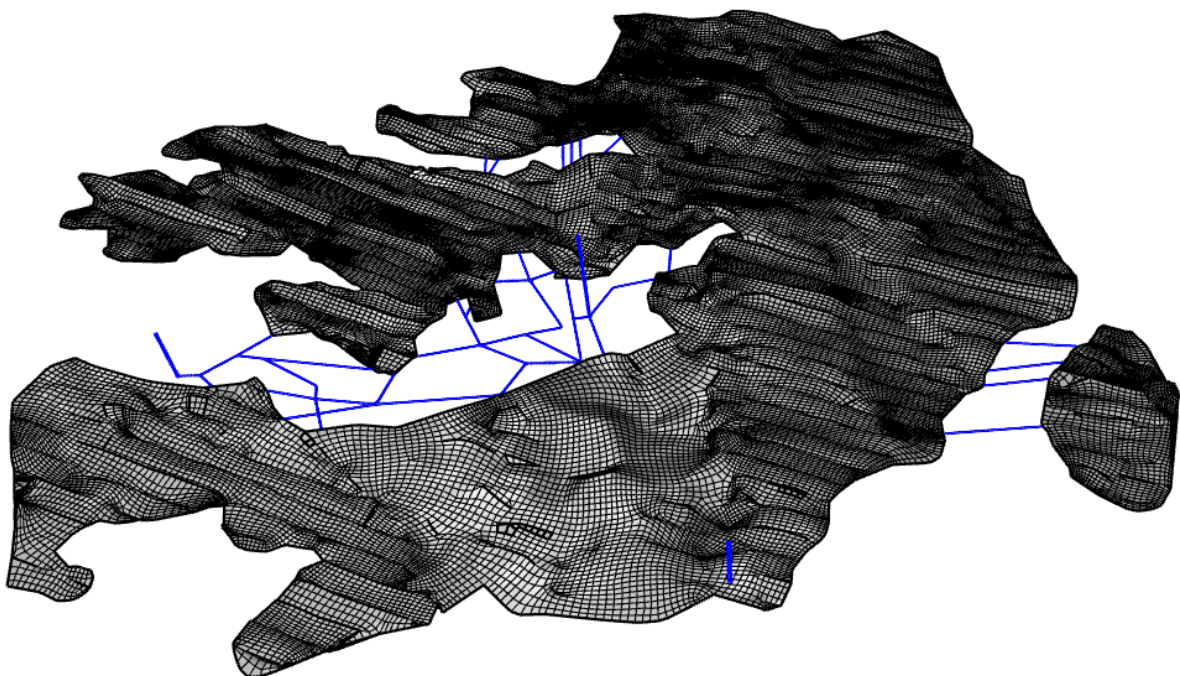


Figure 4: Structural Digital Twin showing the high-resolution NURBS reconstruction of the coal seams integrated with the digitized network of main transport tunnels and vertical shafts (blue lines).

As illustrated in the updated wireframe analysis (Fig. N°4), these elements were georeferenced and integrated directly into the 3D environment, connecting the different levels of the Main Kladno seam. This structural "skeleton" is a critical addition; in an abandoned mine, these voids act as the primary conduits for rising mine water. By including them, the model no longer just represents the ore body, but the actual hydraulic architecture of the site. This level of detail is fundamental for the upcoming Flac3D simulations, as it allows us to accurately track how the flooding front will progress through the galleries before eventually pressurizing the surrounding rock mass.

3.3 Integration of the Tectonic Framework

With the seam geometry locked in, we moved on to layering in the tectonic fault system, relying on historical planimetry and documented dip angles (Fig. N°5). The resulting 3D visualization is a game-changer because it shows exactly how these fault planes slice through and segment the coal layers. This part of the analysis is crucial—it maps out the vertical displacements that define the Kladno basin in a way that 2D maps never could. Seeing the coal seams alongside their respective faults allows us to pinpoint how the mine is compartmentalized. This is the key factor that will ultimately dictate how water pressure distributes itself within the different blocks as the flooding progresses.

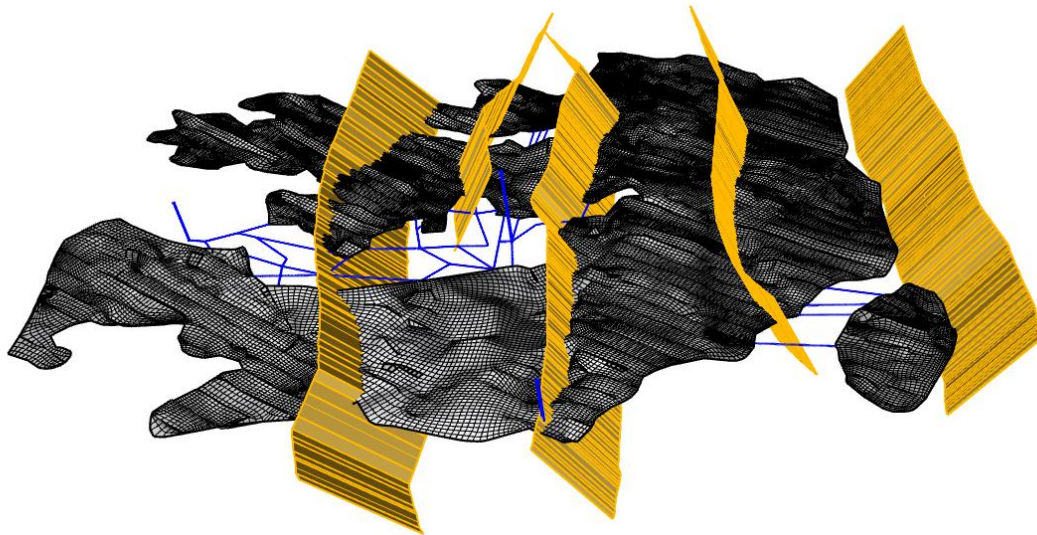


Figure 5: Detail of the tectonic framework: 3D representation of fault planes intercepting the coal seam with documented dip angles.

3.4 High-Resolution Surface Mesh

To establish the upper boundary of our model, we opted for the official DMT 5G digital relief data. This gave us a highly precise topographical baseline derived from airborne LiDAR technology. The advantage here is clear: unlike oversimplified terrain models that smooth out the landscape, this high-resolution mesh preserves the subtle, localized elevation changes across the Tuchlovice area (Fig. N°6). Having such a reliable surface model is vital for the next stages of our work, as it will serve as the primary reference point when we begin comparing our simulated uplift values against the real-world measurements coming in from GNSS and InSAR.

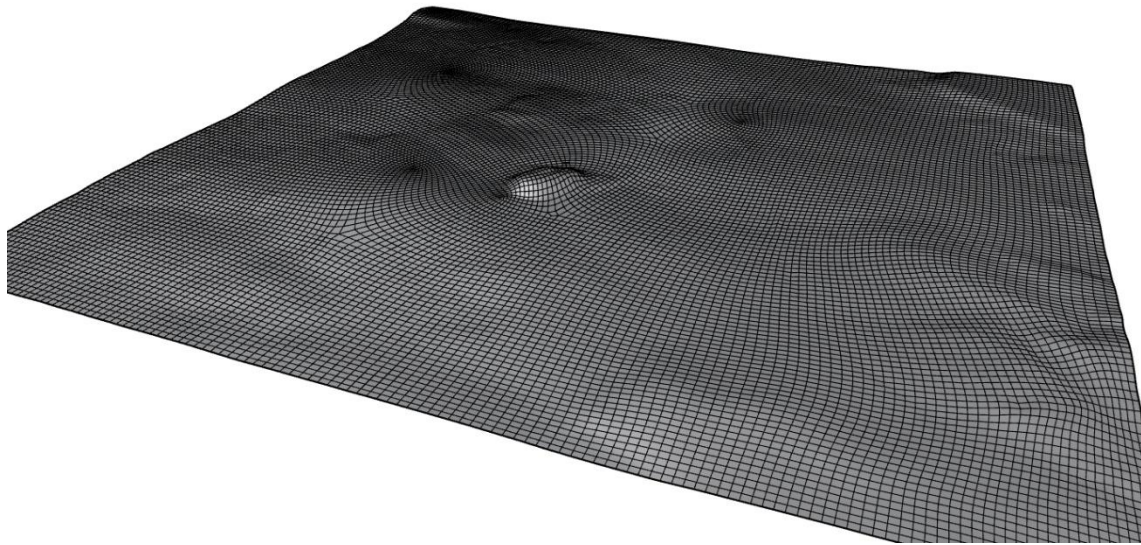


Figure 6: Digital Terrain Model of the Tuchlovice pilot area.

3.5 Integrated Digital Twin

The final stage of the results is the full integration of the surface, faults, tunnels, shaft and coal seams into a single georeferenced environment. As shown in the Fig. N°7, the side-view perspective provides a comprehensive understanding of the spatial relationship between the deep mining voids and the surface topography. This integrated model functions as a "Digital Twin" of the pilot locality, showing exactly how the tectonic discontinuities bridge the gap between the flooded panels and the ground surface. This consolidated geometry represents a ready-to-use foundation for the upcoming numerical simulations, where geomechanical loads and hydraulic pressures will be applied to predict surface deformations.

The final result of this process is a fully integrated, georeferenced environment that brings together the surface, the faults, tunnels, shaft and the coal seams. By looking at the model from a side-view perspective, we can finally get a clear picture of the spatial relationship between the deep mining voids and the surface topography. This 'Digital Twin' does more than just store data; it visually demonstrates how tectonic discontinuities bridge the gap between the flooded mine panels and the ground above. This consolidated geometry is essentially the foundation for our upcoming numerical simulations, where we will apply geomechanical loads and hydraulic pressures to forecast future deformations in Flac3D.

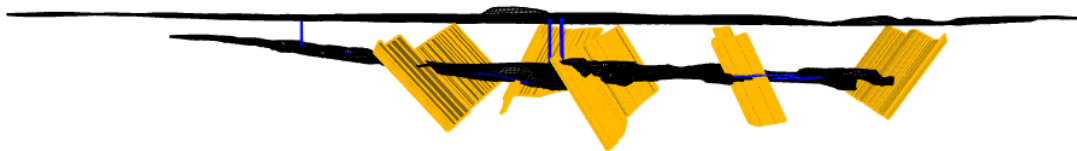


Figure 7: Side view showing the vertical relationship between the DMT 5G surface, the segmented coal seams (in black), tunnels and shaft (in blue) and tectonic faults (in orange).

3.6 Modeling Challenges and Tectonic-Hydraulic Implications

Constructing a digital twin for an abandoned site like Tuchlovice is effectively a forensic exercise. One of the most significant challenges was the reconciliation of legacy data. Working with maps from 2002 and earlier meant dealing with survey techniques that, while accurate for their time, often lack the spatial continuity

required for a 3D NURBS environment. The Python-driven automation was not just a convenience; it was a necessity to filter out inconsistencies where historical elevations of the coal seams conflicted with modern LiDAR-derived surface data.

Beyond the data rescue, the structural interaction between the faults, tunnels, shaft and surface, water introduces a critical variable. During the modeling process, we observed that several major fault planes coincide spatially with surface water body (Loděnice lake) in the pilot Tuchlovice area. From a geomechanical standpoint, this is a major concern. Tectonic faults often act as "highways" for fluid migration. In a flooding scenario, these planes can facilitate the connection between surface water and the underground mine workings, accelerating the increase in pore pressure. This hydraulic connectivity, clearly visible in our 3D side-views, suggests that surface uplift will likely be non-uniform and heavily influenced by the localized "softening" of the rock mass near these fault-lake intersections.

Finally, we must address the temporal challenge of modeling an active process. Unlike a "greenfield" project, Tuchlovice is a dynamic environment where uplift is likely already initiated as the mine water rises. Modeling a site that is already in motion means our geometric basement is not just a static record, but a snapshot of a changing system. The complexity of modeling the "Main Kladno" seam under these conditions—where the mine is already closed and inaccessible—underscores the importance of our 3D approach. By accurately mapping the fault offsets now, we are creating the only tool capable of explaining why certain areas of the Kladno Basin are lifting faster than others, moving beyond simple 2D estimations toward a truly predictive geomechanical model.

4. Conclusion

The reconstruction of the Tuchlovice geomechanical environment represents a critical milestone in moving from static, analog records to a dynamic Digital Twin. By synthesizing disparate data sources—including historical mine plans, the JTSK coordinate system, and airborne LiDAR (DTM 5G)—we have created a robust geometric basement that honors the structural complexity of the Kladno Basin. The use of Rhino 8 and Python-driven automation was not merely a matter of efficiency; it was the only way to ensure the spatial fidelity required to model the non-linear interaction between tectonic faults, tunnels, shafts and mined-out voids.

The primary outcome of this modeling effort is the visual and spatial confirmation that surface uplift is not a uniform phenomenon. Our results explicitly show how the tectonic architecture and fault offsets compartmentalize the mine, creating localized zones of potential deformation. This is particularly relevant where faults intersect surface water bodies, as these planes will likely act as the main drivers for hydraulic pressure distribution during the flooding process. We have effectively replaced 2D assumptions with a precise 3D tool that explains the "why" behind the ground movements observed in the field.

Future Work

The roadmap for the Tuchlovice project is clear. The current geometric model will now be converted into a volumetric mesh for advanced numerical analysis on Flac3D. This transition will allow us to simulate the physical flooding process, applying real hydrostatic loads to the 3D structures we have built. A key component will be modeling the longwall goaf response, specifically tracking the time-dependent mechanical hardening and property degradation of the collapsed rock mass as it reaches saturation. Furthermore, this simulation will be part of a continuous calibration loop, where the predicted uplift values will be compared against active InSAR and GNSS monitoring data. This final step will transform our current model into a predictive instrument for long-term geo-hazard management in the region.

Acknowledgments

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Maden Atık Yönetiminde Yeni Yaklaşım: Piritin Uzaklaştırılması ve Macun Dolgu Uygulaması

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Özet

Madencilik faaliyetleri sonucunda oluşan sülfürlü atıkların çevresel etkilerinin azaltılması, sürdürülebilir atık yönetiminin temel unsurlarından biridir. Artan atık hacimleri ve sülfürlü minerallerin uzun dönemli oksidasyon riski, alternatif ve çevreci bertaraf yöntemlerinin geliştirilmesini gerekli kılmaktadır. Bu kapsamda, atıkların yeraltında değerlendirilmesi hem çevresel hem de işletme güvenliği açısından önem taşımaktadır. Bu çalışmada, yeraltı üretim yöntemiyle işletilen bir metal madeninde cevher hazırlama tesisi kaynaklı atıkların yeniden değerlendirilmesine yönelik bir yaklaşım ele alınmıştır. Flotasyon sonrası piritli atık (PRT) ile piritin uzaklaştırılması sonucu elde edilen piritli atık (FLT) malzemeler karşılaştırmalı olarak incelenmiştir. Atıkların fiziksel, kimyasal ve mineralojik özellikleri yoğunluk, tane boyu dağılımı, XRF ve XRD analizleri ile belirlenmiştir. Flotasyon sonrası FLT malzemedeki kükürt içeriğinin ve özellikle SO₃ oranının belirgin şekilde azaldığı tespit edilmiştir. Bu durum, Asit Maden Drenajı (AMD) oluşum potansiyelinin düşürülmesi açısından önemli bir çevresel avantaj sağlamaktadır. Her iki atık türü çimentolu macun dolgu (ÇMD) üretiminde %5, %7,5 ve %10 bağlayıcı oranlarında değerlendirilmiş ve 7 ile 28 günlük kür sürelerinde tek eksenli basınç dayanımı deneyleri yapılmıştır. Sonuçlar, FLT içeren karışımların daha yüksek dayanım değerleri verdiğini ve %7,5-10 çimento içeriğinde 28 günde 1 MPa'ın üzerinde dayanım sağladığını göstermiştir. Bulgular, piritin uzaklaştırılmasının hem çevresel riski azaltan hem de mühendislik performansını iyileştiren sürdürülebilir bir yaklaşım sunduğunu ortaya koymaktadır.

Anahtar Kelimeler: Flotasyon atıkları, Macun dolgu, Pirit uzaklaştırma, Sürdürülebilir atık yönetimi,

A New Approach to Mine Tailing Management: Pyrite Removal and Paste Backfill Application

Abstract

The mitigation of environmental impacts associated with sulfide-bearing mine tailing is a fundamental component of sustainable mine tailing management. Increasing volumes of tailings and the long-term oxidation risk of sulfide minerals necessitate the development of alternative and environmentally sound disposal strategies. In this context, the utilization of mine tailing as underground backfill material is of particular importance in terms of both environmental protection and operational safety. In this study, a re-evaluation approach was proposed for tailings generated from the mineral processing plant of an underground metal mine. Flotation tailings containing pyrite (PRT) and de-pyritized tailings (FLT), obtained after the removal of pyrite through an additional flotation stage, were comparatively investigated. The physical, chemical, and mineralogical properties of the tailings were characterized by density measurements, particle size distribution analysis, X-ray fluorescence (XRF), and X-ray diffraction (XRD). A

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significant reduction in sulfur content, particularly in SO₃ concentration, was observed in the FLT material following pyrite removal. This reduction represents a substantial environmental benefit in terms of decreasing the Acid Mine Drainage (AMD) generation potential. Both tailing types were utilized in cemented paste backfill (CPB) mixtures with binder contents of 5%, 7.5%, and 10% by weight. Uniaxial compressive strength (UCS) tests were conducted after 7 and 28 days of curing. The results indicated that FLT-based mixtures achieved higher strength values, exceeding 1 MPa at 28 days for 7.5–10% binder content. The findings demonstrate that pyrite removal enhances both environmental performance and mechanical stability, offering a sustainable and technically viable backfilling strategy.

Keywords: Flotation tailings, Cemented paste backfill, Pyrite removal, Sustainable tailing management,

1. Giriş

Madencilik faaliyetleri, doğal kaynakların ekonomik değere dönüştürülmesini sağlarken önemli miktarda atık oluşumunu da beraberinde getirmektedir (Su vd.,2019; Jawadand & Randive, 2021). Özellikle sülfürlü mineraller içeren cevherlerin işletilmesi sonucunda ortaya çıkan pasa ve zenginleştirme atıkları, çevresel açıdan en kritik atık gruplarından birini oluşturmaktadır (Wang vd., 2022). Bu tür atıklar, uygun şekilde yönetilmedikleri takdirde oksidasyon süreçleriyle asidik maden drenajı (AMD) oluşumuna neden olmakta, ağır metal mobilizasyonu, yüzey ve yeraltı su kaynaklarının kirlenmesi, toprak kalitesinin bozulması ve ekosistem fonksiyonlarının zarar görmesi gibi uzun vadeli çevresel sorunlara yol açabilmektedir (Akcil & Koldas, 2006). Sülfürlü atıkların oluşturduğu bu risk, yalnızca işletme süresince değil, maden kapanışı sonrasında da devam eden ve “çevresel miras” niteliği taşıyan bir problem olarak değerlendirilmektedir. Günümüzde düşük tenörlü cevherlerin işletilmesine bağlı olarak birim metal başına üretilen atık miktarının artması, söz konusu çevresel baskının daha da büyümesine neden olmaktadır (Yılmaz & Yılmaz, 2018).

Madencilik sonrası faaliyetlerde temel hedeflerden biri, ortaya çıkan atıkların çevresel etkilerinin azaltılması ve uzun dönemli risklerin kontrol altına alınmasıdır (Aznar-Sánchez vd., 2018). Bu kapsamda, atıkların yüzey depolama alanlarında tutulması yerine yeraltı boşluklarında değerlendirilmesini esas alan çimentolu macun dolgu (ÇMD) uygulamaları, son yıllarda sürdürülebilir atık yönetimi açısından önemli bir alternatif olarak öne çıkmaktadır (Franks vd., 2011; Dang vd., 2025; Sivakugan vd., 2025). ÇMD yöntemi, zenginleştirme atıklarının belirli oranlarda bağlayıcı ile karıştırılarak yeraltı üretim boşluklarına pompalanması esasına dayanmakta, böylece hem yerüstü depolama alanı ihtiyacını azaltmakta hem de atıkların fiziksel olarak stabilize edilmesini sağlamaktadır. Bununla birlikte, sülfür içeriği yüksek atıkların doğrudan macun dolgu karışımlarında kullanılması, uzun vadede kimyasal stabilite ve dayanıklılık açısından bazı riskler barındırabilmektedir (Çinku & Akkaya, 2024). Sülfürlü minerallerin oksidasyonu sonucu oluşabilecek asidik ortam, dolgu malzemesinin dayanımını olumsuz etkileyebileceği gibi çevresel riskleri de artırabilmektedir (Benzaazoua vd., 1999; Benzaazoua vd., 2004).

Yukarıda belirtilen değerlendirmeler çerçevesinde, sülfür içeriğinin düşürülmesine yönelik uygulanacak ön zenginleştirme veya ayırma işlemleri (Ceylan vd., 2014), macun dolgu sistemlerinin uzun dönemli kimyasal stabilitesini artırma ve çevresel risklerini azaltma açısından önemli bir iyileştirme potansiyeli sunmaktadır (Ghirian & Fall, 2017). Flotasyon yöntemiyle pirit gibi sülfürlü minerallerin atıklardan uzaklaştırılması hem asit üretim potansiyelinin düşürülmesi hem de daha stabil bir dolgu malzemesi elde edilmesi açısından yenilikçi ve çevreci bir yaklaşım sunmaktadır. Sülfür oranının azaltılmasıyla birlikte AMD oluşum riskinin minimize edilmesi, macun dolgunun uzun vadeli kimyasal ve mekanik performansını olumlu yönde etkileyebilecek önemli bir parametre olarak değerlendirilmektedir (Liu vd., 2021).

Bu çalışma kapsamında, yeraltı üretim yöntemiyle işletilen bir metal madeninde cevher hazırlama tesisi süreçleri sonucunda ortaya çıkan piritli atık (PRT) ile flotasyon yoluyla piritin uzaklaştırılması sonrası elde edilen piritlessiz atık (FLT) malzemeler incelenmiştir. Atıkların fiziksel, kimyasal ve mineralojik özellikleri belirlenmiş ve sülfür içeriğindeki değişim ortaya konmuştur. Elde edilen malzemeler farklı bağlayıcı oranlarında çimentolu macun dolgu karışımlarında kullanılarak tek eksenli basınç dayanımı deneyleri gerçekleştirilmiştir. Böylece, sülfür içeriği azaltılmış atıkların yeraltı macun dolgu uygulamalarında teknik ve çevresel açıdan kullanılabilirliğinin deneysel olarak değerlendirilmesi amaçlanmıştır. Bu yönüyle çalışma, madencilik sırasında ve sonrasında sülfürlü maden atıklarının yalnızca bertaraf edilmesini değil, çevresel riskleri azaltılarak yeniden değerlendirilmesini esas alan bütüncül bir atık yönetimi yaklaşımı ortaya koymaktadır.

2. Materyal ve Metot

2.1. Materyal

Bu çalışmada, yeraltı üretim yöntemiyle işletilen bir metal madenine ait cevher hazırlama tesisi atıkları kullanılmıştır. Çalışmada Flotasyon sonrası sülfür içeriği yüksek olan ve doğrudan proses çıkışı niteliğindeki atık malzeme (PRT) ile bu malzemenin yeniden flotasyon işlemine tabi tutulmasıyla pirit fazının uzaklaştırılması sonucunda elde edilen, sülfür içeriği azaltılmış atık malzeme (FLT) kullanılmıştır.

Atık malzemelerin fiziksel özellikleri kapsamında yoğunluk, yüzey alanı (blaine) ve tane boyu dağılımı analizleri gerçekleştirilmiştir. Atık malzemelerin yoğunluğu Helyum Piknometre cihazı ile yüzey alanı ise Quantachrome/NOVA Touch LX4 cihazı kullanılarak gerçekleştirilmiştir. Tane boyu dağılımı, lazer difraksiyon yöntemi ile belirlenerek malzemelerin macun dolgu uygulamaları için uygun ince dane dağılımına sahip olup olmadığı değerlendirilmiştir.

Kimyasal bileşim analizleri X-Işını Floresans (XRF) yöntemi ile gerçekleştirilmiş olup başta SiO_2 , Al_2O_3 , Fe_2O_3 , CaO ve SO_3 olmak üzere temel oksit içerikleri belirlenmiştir. Sülfür içeriğindeki değişim özellikle SO_3 oranı üzerinden değerlendirilmiştir. Mineralojik faz analizleri ise X-Işını Kırınımı (XRD) yöntemi ile yapılmış ve pirit başta olmak üzere sülfürlü minerallerin varlığı karşılaştırmalı olarak incelenmiştir.

Bağlayıcı olarak portland çimentosu kullanılmış olup, farklı bağlayıcı oranlarının dayanım üzerindeki etkisini belirlemek amacıyla %5, %7,5 ve %10 (ağırlıkça, kuru atığa göre) çimento içerikli karışımlar hazırlanmıştır. Karışım suyu olarak şebeke suyu kullanılmıştır.

2.2. Macun Dolgu Karışımlarının Hazırlanması

Macun dolgu karışımları, belirlenen bağlayıcı oranlarında atık, çimento ve suyun homojen biçimde karıştırılmasıyla hazırlanmıştır. Araziden elde edilen atık malzemeler ilk olarak homojenleştirme işlemine tabi tutulmuştur (Şekil 1). Homojenleştirme işleminde ayrı ayrı kaplarda bulunan atık malzemeler 100 litrelik beton pan mikserinde karıştırılmıştır. Böylelikle sahadan varillerle gelen malzemeler ile oluşturulacak numunelerde malzeme kaynaklı (tane boyu, kimyasal yapı vb.) olumsuzluklar en aza indirgenmeye çalışılmıştır.



Şekil 1: Atık malzemelerin homojenleştirme işlemi

Karışımlar hazırlanırken hedeflenen kıvam, yeraltına pompalanabilirlik ve segregasyon oluşturmayan, yüksek katı içerikli bir macun yapısı olacak şekilde ayarlanmıştır. Katı oranı ve su/bağlayıcı parametreleri saha uygulamalarına uygun olacak şekilde belirlenmiştir. Hazırlanan karışımların miktarları Tablo 1'de verilmiştir.

Tablo 1: Macun dolgu için tasarlanan deneysel çalışma reçetesi

Karışım Adı	Bağlayıcı oranı (%)	Katı Oranı (%)	Su Miktarı (%)	Kür Süresi (gün)	Çökme Değeri (cm)	Numune sayısı
PRT@5	5					6
PRT@7.5	7.5					6
PRT@10	10					6
FLT@5	5	72	28	7, 28	19-20	6
FLT@7.5	7.5					6
FLT@10	10					6

Macun dolgu numuneleri çimento, atık malzeme ve su karışımından oluşmaktadır. Karışımın (atık malzeme, bağlayıcı ve su) homojen bir şekilde hazırlanması için 10 litre kapasiteli UTEST model mikser kullanılmıştır (Şekil 2a). Bu numunelerden katı malzemeler (atık + çimento) ilk önce mikser içerisinde kuru bir şekilde homojenliği sağlamak için ön karışıma tabi tutulmuştur. Dolgu numuneleri için 5x10 cm boyutunda ve alt kısmında 8 adet 1 mm çapında delik bulunan silindirik kalıplar kullanılmıştır (Şekil 2b). Tüm malzemeler mikser içerisinde homojenite sağlanana kadar (10 dk) karıştırıldıktan sonra slump deneyine tabi tutulmuştur (Şekil 2c). Slump deneyi sonrası istenen kıvam (19-20 cm) sağlandıktan sonra karışım malzemesi dolgu kalıplarına şişleme çubuğu ile her bir katmanda 25 kez olmak kaydıyla 3 ayrı seviyede şişleme işlemi gerçekleştirilerek doldurulmuştur (Şekil 2d). Her bir kür süresi için 3 adet numune hazırlanmıştır.

Hazırlanan karışımlar standart silindirik kalıplara dökülmüş ve laboratuvar ortamında kür koşullarına bırakılmıştır. Numuneler 7 ve 28 günlük kür süreleri sonunda mekanik deneylere tabi tutulmuştur. Kür işlemi, numunelerin nem kaybını önleyecek şekilde kontrollü sıcaklık ve nem koşullarında gerçekleştirilmiştir.



Şekil 2: Macun dolgu karışımında kullanılan mikser (a), dolgu kalıpları ve drenajı (b), slump (çökme) deneyi (c) ve numunelerin kalıba doldurulması (d)

2.3. Mekanik Deneyler

Macun dolgu numunelerinin mekanik performansını belirlemek amacıyla tek eksenli basınç dayanımı (UCS) deneyleri ASTM C 39 (2005) standardında belirtilen yöntemlere göre gerçekleştirilmiştir. Deneyler, ilgili standartlara uygun olarak 50 kN yük kontrollü pres cihazı kullanılarak yapılmıştır. Yükleme hızı sabit tutulmuş (1 mm/dk) ve numunelerin maksimum basınç dayanımı değerleri kaydedilmiştir. Silindirik numunelerin boy/çap oranı 2 olarak belirlenmiş ve test öncesinde numunelerin alt ve üst yüzeyleri dikkatlice düzeltilmiştir. Her bir kür süresi için üç adet numune teste tabi tutulmuş ve sonuçlar bu üç numuneden elde edilen değerlerin ortalaması olarak hesaplanmıştır.

2.4. Deneysel Tasarımın Amacı

Deneysel program, piritin flotasyon yoluyla uzaklaştırılmasının hem kimyasal stabilite (sülfür içeriğinin azaltılması ve AMD potansiyelinin düşürülmesi) hem de mekanik performans (basınç dayanımı gelişimi) üzerindeki etkisini ortaya koymak amacıyla kurgulanmıştır. Bu kapsamda, sülfür içeriği azaltılmış atıkların yeraltı macun dolgu uygulamalarında teknik olarak kullanılabilirliği deneysel verilerle değerlendirilmiştir.

Bu yöntemsel yaklaşım, sülfürlü maden atıklarının yalnızca depolanması yerine ön işlemden geçirilerek daha güvenli ve sürdürülebilir biçimde yeraltında değerlendirilmesine yönelik bütüncül bir atık yönetim modeli sunmaktadır.

3. Bulgular ve Tartışma

3.1. Atık Malzemenin Fiziksel Özellikleri

Bu kısımda atık malzemeler üzerinde yapılan yoğunluk, yüzey alanı ve tane boyu dağılımı deneysel çalışmalarının sonuçları verilecektir. Atıklar üzerinde yoğunluk deneyi 3 kez yapılmış ve ortalama değerleri alınmıştır. Yapılan deney sonrasında atık malzemelerin yoğunlukları Tablo 2’de verilmiştir. Atık malzemelerin yoğunlukları birbirine yakın değerlerde çıkmıştır. FLT atığın yoğunluğu 2.99 iken PRT atığın yoğunluğu 2.93’tür.

Tablo 2: Atık malzemelerin yoğunlukları

Numune	FLT Atık	PRT Atık
1	2.9927	2.9349
2	2.9981	2.9392
3	3.0002	2.9405
Ort.	2.9970	2.9382

Atıkların yüzey alanı değerleri Tablo 3’te verilmiştir. FLT atığın yüzey alanı 8.08486 m²/g iken PRT atığın yüzey alanı 7.29339 m²/g şeklinde hesaplanmıştır. Tane boyu analizi sonuçları irdelendiğinde daha ince tanelere sahip FLT atığın yüzey alanının daha yüksek olması beklenen bir durumdur. Malzemelerin incelik oranı arttıkça yüzey alanında da artış meydana gelmektedir.

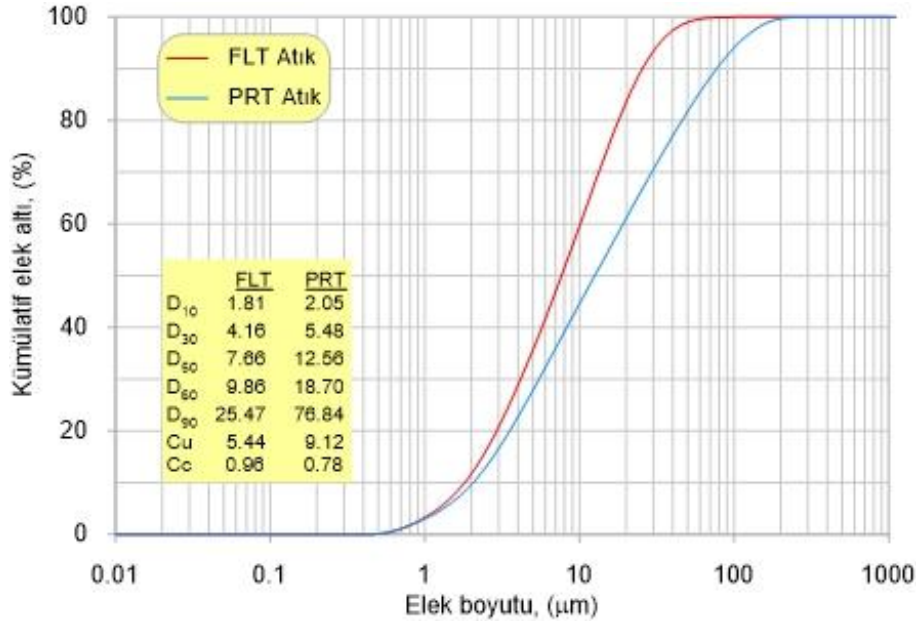
Tablo 3: Atık malzemelerin yüzey alanları

	FLT Atık	PRT Atık
Birim (m ² /g)	8.08486	7.29339

Malvern Mastersizer ile atıklar üzerinde (FLT-PRT) gerçekleştirilen tane boyut dağılımı analizi sonuçlarından elde edilen grafik Şekil 3’te verilmiştir. Grafik incelendiğinde 20 µm altı malzeme miktarının PRT ve FLT atık için sırasıyla ağırlıkça %83.46 ve %61.09 olduğu görülmektedir. Literatürde (Fall vd., 2005) yer alan bilgilere göre ağırlıkça %60’tan fazla <20 µm partiküle sahip atık malzemeye ince, %35-60 arası <20 µm partiküle sahip atık malzemeye orta, %15-35 arası <20 µm partiküle sahip atık malzemeye ise

kaba atıklar denmektedir. Buradan yola çıkarak projede kullanılan FLT ve PRT atık malzemeleri ince atık sınıfına girmektedir. İnce boyutlu malzeme sınıfına giren atıklarla oluşturulan macun dolgu malzemesiyle (%60-90'ı <20 µm) hazırlanan macun dolgu örneklerinin orta boyutlu (%35-60'ı <20µm) ile hazırlananlara göre nispeten daha düşük dayanım verdiği bilinmektedir (Landriault, 1995; Fall vd., 2005).

Malzemelerin ideal tane boyut dağılımına sahip olması için her boyuttan yeterli miktarda tane içermesi önemlidir. Bu durum, uniformluk katsayısının (Cu) 4-6, eğrilik katsayısının (Cc) ise 1-3 arasında olmasıyla sağlanır. Uniformluk katsayısı (Cu) tane boyut dağılımının ne kadar homojen olduğunu gösteren bir parametredir. Cu değeri 4-6 arasında ise tane boyut dağılımı daha homojen hale gelir. Eğrilik katsayısı (Cc) ise tane boyut dağılımının eğriliğini gösteren bir parametredir. Cc değeri 1'e eşit olduğunda tane boyut dağılımı normal dağılıma uymaktadır. Cc değerinin 1'den küçük olması, tane boyut dağılımının ince taneli, 1'den büyük olması ise kaba taneli olduğunu gösterir.



Şekil 3: Atık malzemelerin tane boyu dağılım eğrisi.

Çalışmamızda kullanılan atık malzemelerin tane boyut dağılımı grafiği incelendiğinde, Cu değerinin FLT atık için 5,44, PRT atık için 9,12 olduğu belirlenmiş, Cc değerinin ise FLT atık için 0,96, PRT atık için 0,78 olduğu görülmüştür. Bu değerler, atık malzemelerde ince taneli malzemelerin daha fazla olduğuna ve tam olarak homojen bir tane boyut dağılımına sahip olmadığını göstermektedir.

3.2. Atık Malzemenin Kimyasal Özellikleri

Atık malzemenin kimyasal bileşimini belirlemeye yönelik XRF analizleri Niğde Üniversitesi Merkezi Araştırma Laboratuvarında gerçekleştirilmiş ve Tablo 4'te verilmiştir. XRF analizleri her iki atık (PRT ve FLT) malzemesine de gerçekleştirilmiştir. Atık malzemelerin kimyasal bileşimi incelendiğinde her iki atığın baskın olarak demir oksit (Fe₂O₃), silisyum dioksit (SiO₂), alüminyum oksit (Al₂O₃), kalsiyum oksit (CaO) ve magnezyum oksit (MgO) içerdiği görülmektedir.

Piritin flotasyonu sonrası geriye kalan atık malzemesinde (FLT atık) göze çarpan bir değer ise kükürt trioksit (SO₃) değeridir. Bu değer PRT atıkta %3.717 iken FLT atıkta %1.23'e düşmüştür. FLT atıkta SO₃ oranının belirgin şekilde azalması, piritin flotasyonla etkin biçimde uzaklaştırıldığını ve kükürt değerinin düştüğünü göstermektedir. Bu durum, sülfürlü minerallerin oksidasyonu sonucu oluşabilecek Asit Maden Drenajı (AMD) riskinin düşürülmesi açısından önemli bir avantajdır. Macun dolguda kimyasal stabilite ve uzun vadeli dayanıklılık açısından düşük sülfür içeriği tercih edilir. Bu nedenle FLT atığın, çevresel performans bakımından daha uygun görüldüğü söylenebilir.

Her iki atık da yüksek silikat içeriğine sahiptir. Bu durum, doğrudan bağlayıcı olmasalar da çimento hidrasyonu sonrası oluşan Ca(OH)₂ ile sınırlı pozzolanik reaksiyon potansiyeli gösterebileceklerini düşündürmektedir. PRT'nin daha yüksek SiO₂ içeriği teorik olarak daha fazla inert dolgu davranışı

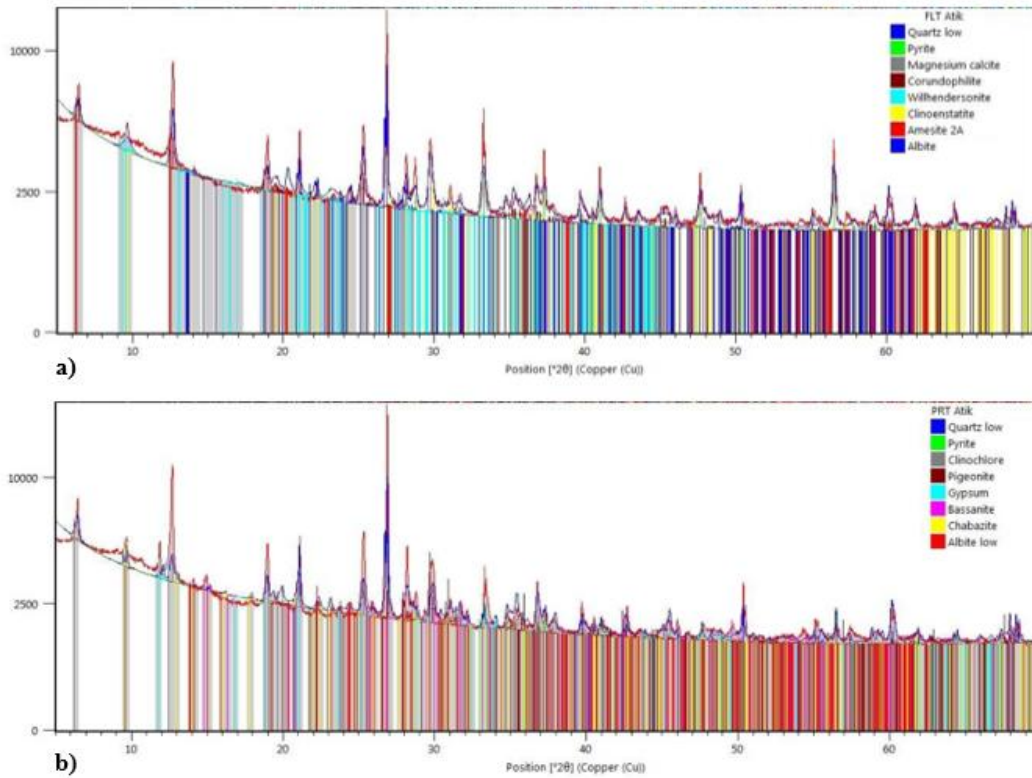
sağlayabilir, fakat kimyasal stabilite açısından sülfür içeriği daha belirleyicidir. SiO₂ değeri PRT atıkta %43.72 iken FLT atıkta %34.45'tir. Atıklardaki Al₂O₃ değeri birbirine yakın görünmektedir. PRT atıkta %9.39 iken FLT atıkta %8.71'dir. MgO değeri ise her iki atıkta birbirine oldukça yakındır ve %7 mertebelerindedir.

Tablo 4: Atıkların kimyasal bileşenleri

Bileşen	PRT Atık	FLT Atık
	(%)	(%)
Fe ₂ O ₃	14.199	15.528
SiO ₂	43.718	34.45
Al ₂ O ₃	9.392	8.714
CaO	10.376	7.631
MgO	7.972	7.424
Mn ₃ O ₄	1.146	0.966
SO ₃	3.717	1.23
Na ₂ O	1.003	0.843
K ₂ O	0.603	0.508
L.O.I.	7.177	22.14

3.3. Atık Malzemenin Mineralojik Özellikleri

Atık malzemelerin mineralojik bileşimini belirlemeye yönelik XRD analizleri Niğde Üniversitesi Merkezi Araştırma Laboratuvarında gerçekleştirilmiş ve her iki atığın da içerdiği mineraller belirlenerek Şekil 4'te verilmiştir. Şekil incelendiğinde her iki atıkta da kuvars, pirit ve albit ortak olarak bulunmaktadır. FLT atıkta piritin daha az miktarda yer aldığı ve kalsit miktarını daha fazla olduğu görülmektedir.



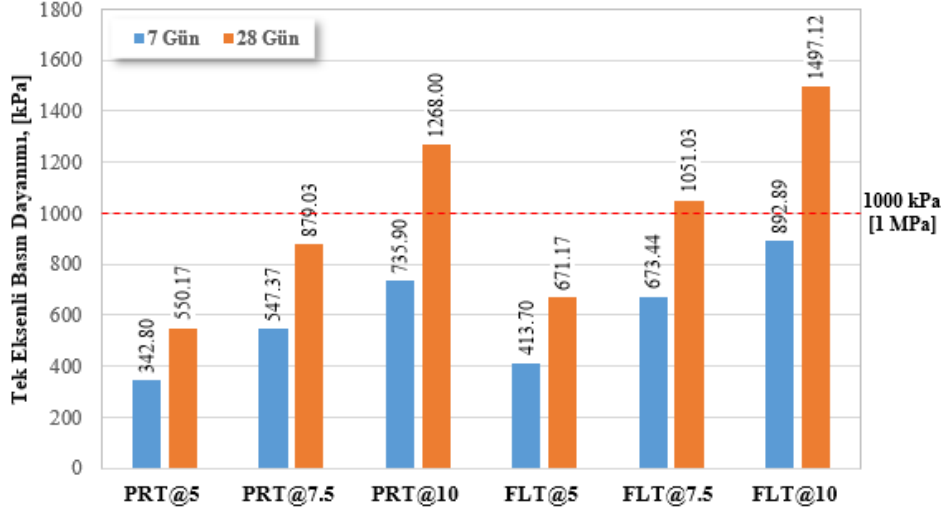
Şekil 4: Atık malzemelerin XRD paternleri a) FLT, b) PRT

XRD analizleri, her iki atığın baskın olarak kuvars ve feldspat grubu silikat minerallerinden oluştuğunu göstermiştir. PRT atığında pirit piklerinin belirgin olması, sülfürlü fazların varlığını doğrularken, flotasyon sonrası elde edilen FLT atığında bu piklerin önemli ölçüde azaldığı gözlenmiştir. Ayrıca PRT numunesinde sülfat fazlarına ait piklerin varlığı dikkat çekmektedir. Bu bulgular, flotasyon işleminin sülfürlü minerallerin uzaklaştırılmasında etkin olduğunu ve FLT atıkların kimyasal olarak daha stabil bir yapı sergilediğini ortaya koymaktadır. Mineralojik karakterizasyon sonuçları, kimyasal analiz ve mekanik dayanım verileri ile uyumlu olup, sülfür içeriği azaltılmış atıkların macun dolgu uygulamalarında daha uygun bir malzeme olduğunu desteklemektedir.

3.4. Karışımların Dayanım Özellikleri

Toplam 36 adet silindirik ÇMD numunesi üzerinde gerçekleştirilen UCS deneylerinden elde edilen sonuçların grafiksel gösterimi Şekil 5'te verilmiştir. Grafikler incelendiğinde, her iki atık türü için de kür süresinin artmasına bağlı olarak dayanım değerlerinde belirgin bir artış olduğu görülmektedir. 7 ve 28 günlük sonuçlar karşılaştırıldığında, tüm karışım gruplarında hidrasyon sürecine bağlı olarak anlamlı bir dayanım gelişimi meydana geldiği anlaşılmaktadır. Örneğin, %5 bağlayıcı içeren PRT@5 numunesinin dayanımı 7. günde 342.80 kPa iken, 28. günde 550.17 kPa'ya yükselmiştir. Benzer şekilde, FLT@5 numunesinde 7 günlük dayanım 413.70 kPa olarak ölçülmüş, 28 günlük kür sonunda ise 671.17 kPa değerine ulaşmıştır. Bu artış, çimento hidrasyon ürünlerinin zamanla gelişerek dolgu matrisi içerisinde daha bütüncül ve dayanıklı bir yapı oluşturduğunu göstermektedir.

Ayrıca, FLT atıklarının kullanıldığı karışımların hem 7 hem de 28 günlük kür sürelerinde PRT atıklı karışımlara kıyasla daha yüksek UCS değerleri verdiği belirlenmiştir. Örneğin, %10 bağlayıcı içeren karışımlarda PRT@10 numunesi 28. günde 1268.00 kPa dayanım sağlarken, FLT@10 numunesi aynı sürede 1497.12 kPa değerine ulaşmıştır. Bu sonuçlar, pirit uzaklaştırma işleminin dolgu matrisinin mekanik performansını olumlu yönde etkilediğini ve sülfür içeriği azaltılmış atıkların daha yüksek dayanım gelişimi potansiyeline sahip olduğunu ortaya koymaktadır.



Şekil 4: Macun dolgu numunelerinin dayanım değerlerinin grafiksel gösterimi

Her iki atık türünde de bağlayıcı oranının artmasıyla birlikte tek eksenli basınç dayanımında belirgin bir artış gözlenmiştir. %5, %7,5 ve %10 çimento içeren karışımlar karşılaştırıldığında, daha yüksek çimento içeriğinin dolgu matrisinde daha fazla hidrasyon ürünü oluşumunu sağlayarak mekanik performansı iyileştirdiği görülmektedir. Bu durum literatürle desteklenmektedir. Fall ve Benzaazoua (2005), çimento dozajındaki artışın macun dolgu sistemlerinde hem mekanik dayanım gelişimini hem de kimyasal dayanıklılığı iyileştirdiğini belirtmiştir. Artan bağlayıcı içeriği, hidrasyon reaksiyonları sonucunda daha yüksek miktarda kalsiyum-silikat-hidrat (C-S-H) jel fazının oluşmasına yol açmakta; bu durum dolgu matrisinin daha yoğun ve bütüncül bir mikro yapı kazanmasını sağlamaktadır. Gelişen C-S-H ağı, kapiler boşluk oranını ve bağlantılı poroziteyi azaltarak geçirgenliği düşürmekte, böylece asidik ve sülfatlı

ortamlarda iyon taşınımını sınırlandırmaktadır. Bu mikro yapısal iyileşme, özellikle sülfürlü atık içeren macun dolgularında pirit oksidasyon hızının ve buna bağlı asit üretim potansiyelinin azaltılmasına katkı sağlamaktadır.

Bağlayıcı oranının artırılması her ne kadar dayanım ve dayanıklılık performansını artırsa da çimentonun macun dolgu maliyetindeki yüksek payı nedeniyle ekonomik açıdan dikkatle optimize edilmesi gereken bir parametredir. Klein ve Simon (2006) ile Erçıkıd (2009), teknik gereksinimleri karşılayan minimum bağlayıcı oranının belirlenmesinin hem mühendislik performansı hem de maliyet etkinliği açısından kritik olduğunu vurgulamıştır. Bu nedenle bağlayıcı dozajı, mekanik dayanım, kimyasal stabilite ve ekonomik sürdürülebilirlik kriterleri birlikte değerlendirilerek tasarlanmalıdır.

28 günlük kür süresi sonunda, PRT@10 ile FLT@7,5 ve FLT@10 numuneleri 1.0 MPa'nın üzerinde dayanım değerlerine ulaşmıştır. Buna karşılık, her iki atık türünde de %5 çimento içeren karışımların 28 günlük dayanımları 1.0 MPa'nın altında kalmıştır. Çimento oranının %5'ten %7,5-10 aralığına yükseltilmesi, özellikle 28 günlük dayanım performansında belirgin bir iyileşme sağlamıştır. Bu çalışmada 1.0 MPa eşiği, literatürde serbest duran macun dolgu uygulamaları için 28 günlük kür sonunda önerilen ve üretim alanına bitişik stopların kendi kendini taşıyabilmesi açısından yeterli kabul edilen dayanım kriterine dayandırılmıştır.

PRT atıkları pirit içeriğinden dolayı AMD riskini taşır (Alemdağ vd., 2020a; Alemdağ vd., 2020b), bu da uzun vadede (360 güne kadar) dayanımda kayıplara yol açabilir (Erçıkıd vd., 2009). Bu durum, PRT atıklarının uzun vadede dayanım kaybı yaşama riskinin daha yüksek olduğunu ve FLT atıklarının çevresel ve mekanik dayanım açısından daha avantajlı olduğunu göstermektedir. FLT atıkları ile %7.5 ve %10 çimento oranlarında oluşturulan macun dolgu numunelerinin 28 günlük kür süreleri sonunda elde edilen dayanım değerleri hedef dayanım olan 1 MPa'nın üzerinde gerçekleşmiştir ve ilerleyen kür sürelerinde bu dayanım artışının devam edeceği belirlenmiştir.

Sonuç olarak, FLT atıklarının yeraltı madencilğinde macun dolgu malzemesi olarak kullanımı, dayanım performansı ve çevresel sürdürülebilirlik açısından daha üstün bir tercih sunmaktadır. Bu çalışmada elde edilen dayanım verileri, yeraltı stabilite analizlerinde kritik bir rol oynayacak olup, bu verilerin dikkate alınması, güvenli ve sürdürülebilir madencilik uygulamaları için gereklidir.

4. Sonuçlar

Bu çalışmada, yeraltı üretim yöntemiyle işletilen bir metal madeninde cevher hazırlama tesisi kaynaklı piritli atıkların (PRT) flotasyonla piritinin uzaklaştırılması sonrası elde edilen piritlessiz atıkların (FLT), çimentolu macun dolgu (CMD) üretiminde kullanım potansiyeli araştırılmıştır. Elde edilen bulgular aşağıdaki şekilde özetlenebilir:

- Kimyasal ve mineralojik açıdan, flotasyon sonrası FLT malzemede toplam kükürt ve özellikle SO₃ içeriğinde belirgin bir azalma tespit edilmiştir. Bu durum, Asit Maden Drenajı (AMD) oluşum potansiyelinin düşürülmesi açısından önemli bir çevresel avantaj sağlamaktadır. XRD analizleri de pirit pik şiddetlerinin FLT numunelerde azaldığını doğrulamıştır.
- Mekanik performans açısından, her iki atık türünde de kür süresinin artmasıyla tek eksenli basınç dayanımında artış gözlenmiştir. Ancak FLT içeren karışımlar, hem 7 hem de 28 günlük kür sürelerinde PRT içeren karışımlara kıyasla daha yüksek dayanım değerleri göstermiştir.
- Bağlayıcı oranının etkisi, dayanım gelişiminde belirleyici olmuştur. %7,5 ve %10 çimento içeren FLT karışımları 28 günlük kür sonunda 1 MPa'nın üzerinde dayanım sağlayarak yeraltı kendini taşıyan dolgu uygulamaları için yeterli performans göstermiştir. %5 çimento içeren karışımlar ise her iki atık türünde de bu eşik değerin altında kalmıştır.
- Piritin flotasyonla uzaklaştırılması, yalnızca çevresel riski azaltmakla kalmamış, aynı zamanda dolgu sisteminin mekanik performansını da iyileştirmiştir. Azalan sülfür içeriği, potansiyel sülfat oluşumu ve uzun vadeli dayanım kaybı riskini sınırlayabilecek niteliktedir.

Sonuç olarak, flotasyonla pirit uzaklaştırma işlemi sonrasında elde edilen atıkların yeraltı macun dolgu uygulamalarında değerlendirilmesi, atık depolama yükünü azaltan, AMD riskini düşüren ve mühendislik performansını artıran bütüncül ve sürdürülebilir bir atık yönetimi yaklaşımı sunmaktadır. Bu yaklaşım, madencilik sonrası faaliyetler ve döngüsel ekonomi ilkeleri kapsamında teknik olarak uygulanabilir ve çevresel açıdan avantajlı bir alternatif olarak değerlendirilebilir.

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Mazıdağı Eti Gübre ve Metal Geri Kazanım Tesislerinde, Küre Cevheri Pirit Konsantresinden Co, Cu, Zn, Au ve Fe üretimi: Sıfır Atık Uygulaması

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Özet

Küre Bakır cevheri, Ceneviz ve Osmanlı İmparatorluğu döneminden beri üretilmektedir. 1980'lerde ETİBANK yeni bir konsantratör devreye aldı. Burada 2016 yılına kadar sadece bakır üretimi yapılmış ve pirit içeriği değerlendirilememiştir. Pirit içinde bakırın yanı sıra kobalt, çinko ve altın gibi önemli metallerin varlığı bilinmesine rağmen, ekonomik bir çözüm bulunamamıştır. Mazıdağı'nda kurulan entegre bir tesisle Eti Bakır AŞ, bu pirit konsantresini ve içindeki önemli metalleri ekonomiye kazandırmakla kalmamış, aynı zamanda Mazıdağı'ndaki fosfat yataklarından gübre üretimi için gerekli sülfürik asit ihtiyacını da karşılamıştır. Bu tesiste, gübre üretimi için gerekli olan sülfürik asit elde etmek amacıyla pirit akışkan yataкта kavrulmakta, kavrulma işleminden elde edilen kalsin ise basınç altında liç ve solvent ekstraksiyonu uygulanarak elde edilmektedir. Sonuç olarak, önemli metal içeriğine sahip Küre Pirit, Mazıdağı entegrasyon tesisinde değerlendirilmektedir. Bu bağlamda, bakır katot bakır olarak kobalt ve çinko karbonat formunda üretilmektedir. Altın ise CIP yöntemiyle ham altın olarak elde edilmektedir. CIP sonrası satın alınan küspe, demir ve çelik endüstrisi için uygun saflık ve kalitede olup, halen yurt dışına satılmaktadır. Tesiste işlenen piritten hiçbir atık oluşmamaktadır. Bu, birçok hammadde için örnek teşkil eden sıfır atık bir tesistir. Bu sunumda, pirit değerlendirmesi kapsamındaki süreçler ve bu süreçlerin uygulama sonuçları hakkında genel bilgiler verilmektedir.

Anahtar Kelimeler: Pirit, Sıfır atık, Kobalt, Bakır, Çinko ve altın geri kazanımı

Production of Co, Cu, Zn, Au and Fe from pyrites concentrate of Küre Concentrator in Mazıdağı Fertilizer & Metal Recovery Plant: Zero tailing application

Abstract

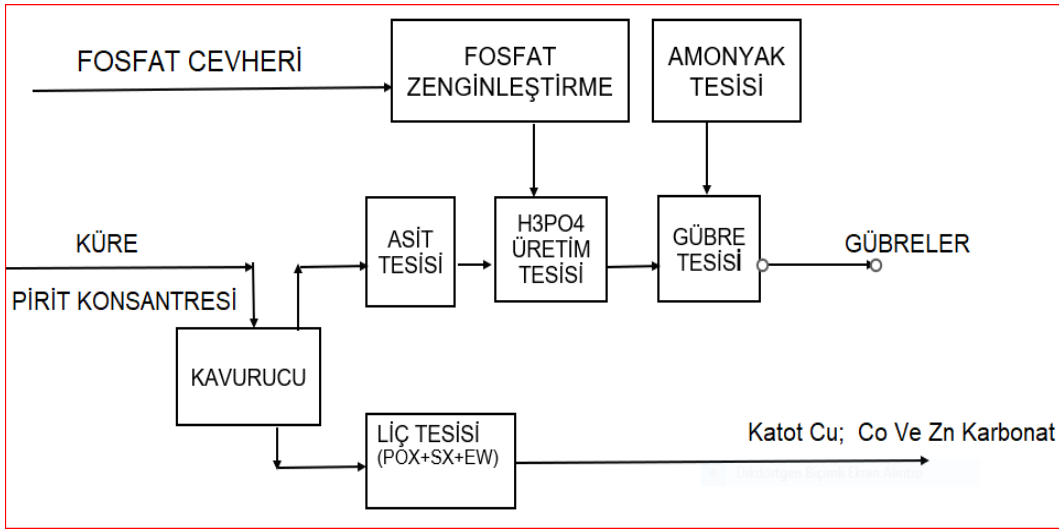
Küre Copper ore has been produced in the globe since the Genoese and Ottoman Empire period. In the 1980s, ETİBANK commissioned a new concentrator. Here, only copper was produced until 2016, and pyrite contents could not be evaluated. Although the existence of important metals such as cobalt, zinc and gold other than copper in pyrite is known, no economic solution has In an integrated facility established in Mazıdağı, Eti Bakır AŞ not only brought this pyrite concentrate and the important metals in it to the economy, at the same time, it met the need for sulfuric acid for the production of fertilizer from phosphate deposits in Mazıdağı. In this plant, pyrite was roasted in a fluidized bed to produce sulfuric acid, which is necessary for fertilizer production, while calcine, which was obtained from roasting, was obtained by leaching under pressure and applying solvent extraction. As a result, Küre Pyrite, which has important metal contents, is evaluated in the Mazıdağı integration facility. In this context, copper is produced as cathode copper, in the form of cobalt and zinc carbonate. Gold, on the other hand, is earned as raw gold with CIP. The cake purchased after CIP is of suitable purity and grade for the iron and steel industry and is still sold abroad. The cake purchased after CIP is of suitable purity and grade for the iron and steel industry and is still sold abroad. There is no waste from the pyrite processed in the facility. This is an exemplary zero waste

facility for many raw materials. In this presentation, general information about the processes within the scope of pyrite evaluation and the application results of the processes are given.

Keywords: Pyrite, Zero waste, Cobalt, Copper, Zinc and gold recovery

1. Giriş

Bu tesis, ana ürünü gübre olan ve ETİ Bakır Küre Tesisi'nin kavrulmuş pirit konsanresinden bakır katot, kobalt ve çinko karbonat üreten çok ürünlü bir tesistir. Pirit cevheri, sülfürik asit üretimi için gerekli olan SO₂ içeren gazı üretmek üzere bir kavurma fırınına beslenir. Sülfürik asit daha sonra gübre üretiminde kullanılır ve az miktarda asit hidrometalurjik liç işlemine gider. ETİ Bakır Mazıdağı Fosfat Tesisi'ndeki ana proses genel akım şeması Şekil 1'de gösterilmiştir (Canbazoğlu vd..2019).



Şekil 1: Mazıdağı Gübre ve Metal Geri Kazanım Entegre Tesisi Genel Akım Şeması

Kavurma fırını ve sülfürik asit tesisinin mühendislik aşamasından sonra, kavrulmuş kalsinede önemli miktarda kobalt, bakır ve çinko tespit edildikten sonra hidrometalurjik liç prosesi kurulmuştur. Bu değerli metalleri geri kazanmak için, kalsine liç prosesi ETİ Bakır Araştırma Merkezi tarafından kendi bünyesinde incelenmiş ve Outotec tarafından Finlandiya'nın Pori kentindeki araştırma merkezinde geliştirilmiştir (Karonen vd., 2015). İnşaat 2016 yılının başlarında başlamış ve devreye alma 2018 yılının ilk çeyreğinde başlamıştır. Seyrankaya (2019), kalsine basınçlı liç koşullarını doğrulamış ve Karonen vd. (2015) ile aynı liç koşullarını ve metal geri kazanım sonuçlarını bulmuştur.

2. Kalsin Liç Prosesi

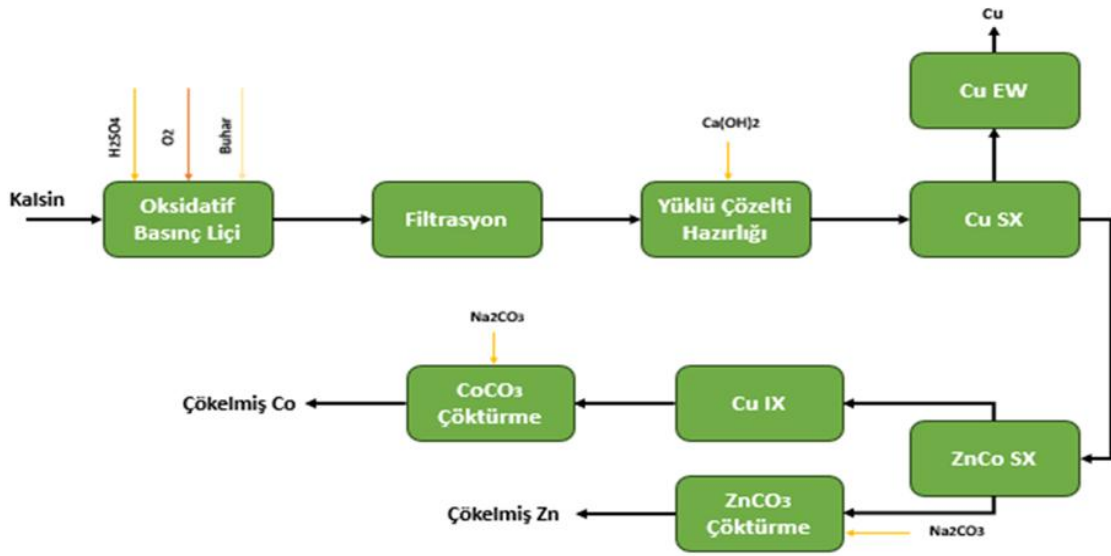
ETİ Bakır'ın hidrometalurjik liç prosesi, 870 °C'de üretilen kavrulmuş kalsinin asidik ortamda bulamaç haline getirilmesiyle başlar; bu işlemde kalsin yaklaşık %50 katı madde içeren bir bulamaç haline dönüştürülür. Tablo 1, cevherden geri kazanılacak değerli metallerin elementel bileşimini özetlemektedir. Saatte 50 ton tasarım kütle akış kapasitesine sahip kalsin bulamacı daha sonra liç için otoklav devresine beslenir.

Basınçlı liç aşaması, iki aşamalı ön ısıtma, bir otoklav, iki aşamalı buharlaştırma/enerji geri kazanımı ve bir havalandırma gazı yıkama sisteminden oluşmaktadır. Kalsin bulamaç, otoklav liçinden önce seri olarak iki aşamalı ön ısıtmaya beslenir. Otoklav ise, VSD kontrollü karıştırıcılar ve ayrı yüksek basınçlı buhar ve oksijen hatları ile donatılmış beş bölmeli bir kaptır. Sülfürik asit, önceden ısıtılmış bulamaçla birlikte ilk bölmeye enjekte edilir ve aynı anda yüksek basınçlı buhar ve oksijen eklenir. Otoklav tasarım koşulları, 220 °C ve 27 barda ve çıkışta 50-60 g/L asit konsantrasyonunda olacak şekilde seçilmiştir. İkinci aşama buharlaştırma. Ön ısıtıcıların ve otoklavın gaz çıkışları, atmosfere salınmadan önce gaz arıtma sisteminde

işlenir. Basınçlı liç akışındaki yapı malzemesinin yüksek basınca, sıcaklığa ve yüksek asitli koşullara dayanacak şekilde üretilmesi sağlanır (Haavanlammi vd., 2019).

Tablo 1: ETİ Bakır AŞ kalsin analizi

Element	%
Fe	55 – 65
Co	0,7 – 1,3
Cu	0,5 – 0,9
Zn	0,1 – 0,5



Şekil 2: Mazıdağı Hidrometalurji Tesisi Genel Akım Şeması

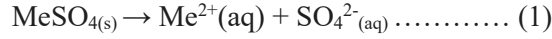
Süzülmüş kalsin bulamacı, kekin ham sıvıdan ayrılması için filtrasyona tabi tutulacaktır. Filtrasyon devresinden elde edilen süzüntü ve yıkama süzüntüsü, ham kalsin için hamurlaştırma çözeltisi olarak kullanılacak ve doyunmuş liç çözeltisi (Pregnant leach solution, PLS) arıtma tesisine besleme malzemesi olarak hizmet edecektir.

PLS daha sonra kalsiyum hidroksit ile işlenerek ham sıvının asit konsantrasyonu düşürülür. İşlenmiş sıvı daha sonra bir yoğunlaştırıcıya gönderilir ve taşan çözelti, bakır çözücü ekstraksiyonu ve elektro kazanımından önce bir parlatma filtresine beslenir. Bakır rafınatı (CoZn açısından zengin çözelti), CoZn çözücü ekstraksiyonundan önce devredeki toplam demiri uzaklaştırmak için demir giderme devresine beslenir. Devrede demir, pH hedefi 4,2-4,5 olan kalsiyum hidroksit yardımıyla uzaklaştırılır. Demir içermeyen CoZn çözeltisi bir yoğunlaştırıcıya gönderilir ve taşan çözelti, Co ve Zn'nin ayrıldığı CoZn çözücü ekstraksiyonu ve sıyırma aşamasından önce parlatma filtresine beslenir. Son aşamada, Zn açısından zengin çözelti bir reaktörde sodyum karbonat ile karıştırılarak Zn karbonat üretilirken, Co açısından zengin çözelti, çözeltide kalan Cu'yu ayırmak için bir iyon değişim kolonuna gönderilir. Cu içermeyen Co çözeltisi daha sonra sodyum karbonat yardımıyla kobalt karbonat oluşturulan bir reaktöre gönderilir. CoZn rafınatı, proses atık suyu arıtımı için son nötralizasyon akışına gönderilir. Şekil 2, ETİ Bakır'ın hidrometalurjik kalsin liç prosesini özetlemektedir.

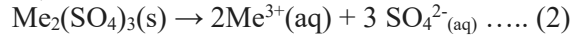
2.1. Otoklav liç reaksiyonları

Basınç altında okijenin kullanıldığı yükseltgen ortamda liç sırasında aşağıdaki ana reaksiyonlar meydana gelir (Karonen vd., 2015) S = Katı faz; Aq = Sıvı Faz)

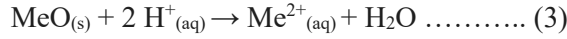
Me²⁺ (Cu, Co, Zn, Fe) sülfat çözünmesi:



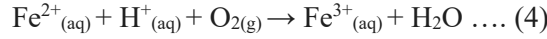
Me³⁺ (Al, Fe) sülfat çözünmesi:



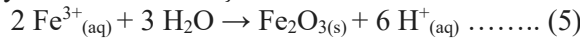
Asit ile metal oksit (Cu, Co, Zn) liçi:



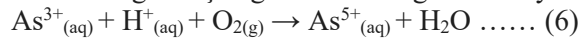
Demir (II) iyonunun demir (III) iyonuna oksidasyonu:



Demir (III) iyonunun hematite çökmesi:



Üç değerlikli arseniğin beş değerlikli arseniğe oksidasyonu:

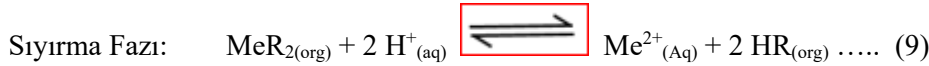
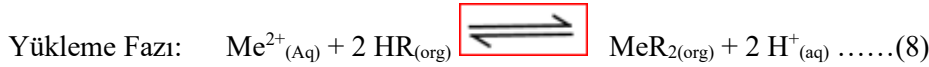


Arseniğin demir (III) arsenat olarak çökmesi:



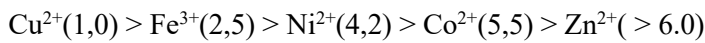
3.Çözeltilerden Cu, Zn, Co metallerin Solvent Ekstraksiyon ile Kazanılması

Yüklü çözeltilerden Cu, Zn ve Co' ın kazanılması sırasında aşağıdaki ana reaksiyonlar meydana gelir (Ritcey ve Ashbrook, 1984; BASF, 2015) (Org= Organik faz):



Burada: Me²⁺ (Cu, Co, Zn); HR (organik faz); H⁺ (Asidik ortam, sülfat/klorür) ifade etmektedir.

Mazıdağı Tesisinde bakırın çözücü ekstraksiyonu için LIX 984 N kullanılmaktadır. 860N-IC ve LIX 84-IC'nin 1:1 hacim oranında karıştırılmasıyla elde edilen bu reaktif, demir, çinko ve kobalt varlığında bakır için seçici olan, yüksek parlama noktasına sahip bir hidrokarbon seyreltici içinde '5-nonilsalisilaloksim ve 2-hidroksil-5-nonil-asetofenon oksim' karışımıdır. Sülfatlı çözeltilerden LIX 984 N ile metal seçicilik sırası ve pH₅₀ değerleri aşağıdaki gibidir (BASF, 2019):



3.1.Bakır Solvent Ekstraksiyonu (CuSX)

Cu SX işleminde, devrede dahili nötralizasyonlu üç ekstraksiyon aşaması, bir yıkama aşaması, iki sıyırma aşaması ve yüklü bir organik tank bulunur. Cu SX'in üretim çözeltisi olan zengin elektrolit için, elektrolit sirkülasyon tanklarından önce bir çöktürme tankı ve çift ortamlı filtreler de mevcuttur. Cu SX'in sıyırma aşamasından alınan zengin bakır çözeltisinden, elektro kazanma (elektroliz) ile Fe, Pb, S ve O gibi başlıca safsızlıkların düşük seviyelerine olan %99,9979'un üzerinde saflığa sahip 'A sınıfı bakır katot' üretilmektedir (Şekil 3). Yıllık 2000 ton katot bakır üretilmektedir.



Şekil 3: Mazıdağı tesislerinde katot bakır üretimi

3.2. Çinko Kobalt Solvent Ekstraksiyonu

CYANEX 272, Mazıdağı Tesisinde Kobalt ve Çinko'nun çözücü ekstraksiyonunda kullanılmaktadır. CYANEX 272'nin aktif bileşeni 'bis(2,4,4-trimetilpentil) fosfinik asit'tir. Bu organik, kalsiyum ve kobaltın varlığında çinko için seçicidir. Metal seçicilik sırası ve pH_{50} değerleri aşağıdaki gibidir (Solvey, 2008; Cytec, 2010; Ritcey, 2006; Cole ve diğerleri, 2006):

$Fe^{3+}(1,17) > Zn^{2+}(1,84) > Al^{3+}(2,68) > Cu^{2+}(3,2) > Mn^{2+}(3,48) > Co^{2+}(3,77) > Mg^{2+}(4,57) > Ca^{2+}(4,9) > Ni^{2+}(6,74)$

Cu SX ve EW devresinden elde edilen rafinat daha sonra demir giderme akışına gönderilir. Rafinatı, pH'ı 4,2-4,5'e getirmek için kireç sütü kullanılır. Ardından bulamaç koyulaştırılır ve taşan çözelti, CoZn SX'e verilmeden önce bir arıtma filtresine beslenir. ETİ Bakır'ın CoZn SX tesisi, bir kerosen yıkama aşaması, dört ekstraksiyon aşaması, iki organik yıkama aşaması, dört kobalt sıyırma aşaması, iki çinko sıyırma aşaması, boş organik tank, organik ön nötralizasyon reaktörü, üretim çözeltisi son çöktürme tankları, üretim çözeltisi organik giderme filtreleri ve tortu arıtma işleminden oluşmaktadır. Karıştırıcı çöktürme tankları, son çöktürme tankları ve organik giderme filtreleri Outotec'in tescilli ekipmanlarıdır. Boş organik tank ve ön nötralizasyon reaktörü tasarımları da Outotec tarafından yapılmıştır.



Şekil 4: Çinko Karbonat Tikneri

CoZn SX prosesinden iki üretim çözeltisi elde edilir; Co çözeltisi ve Zn çözeltisi. Co çözeltisi, kobalt çöktürmesinden önce bakır uzaklaştırma işlemine gönderilir. Co çözeltisinden bakır uzaklaştırma işlemi iyon değişim kolonları ile yapılır. Son aşamada kobalt ve çinko, sodyum karbonat ile ayrı metal karbonat tuzları olarak çöktürülür. Bu işlemler sonunda; 900 ton çinko metale karşı gelen $ZnCO_3$ ile 2250 ton kobalta karşı gelen $CoCO_3$ üretilmektedir (Şekil 4 ve Şekil 5).



Şekil 5: Kobalt Karbonat Tikneri

4. Otoklav Liçi Katı Atıklarının Değerlendirilmesi

Otoklavdan alınan pülp filtrelerde süzildükten sonra elde edilen çözelti doğrudan Cu Zn ve Co tın kazanılması için solvent Ekstraksiyon ünitelerine gönderilirken, katı malzeme, diğer bir ifadeyle liç keki, kekte bulunan Au ve Ag ün kazanılması için siyanür liçine tabi tutulmaktadır. Altın % 85 Gümüş ise, % 15'lik verimlerle kazanılmaktadır. Yıllık 500 kg altın üretimi söz konusudur (Şekil 6).

Siyanürleme işlemi sonrası kalan atık ise, sanayide demir üretimine uygun, emprüte içermeyen ve %62- 65 Fe içeren, mineralojik olarak ağırlıklı olarak hematitten oluşan, bir hammadedir. Miktarı yıllık 350.000 tondur. Bu hammadde için Mazıdağı entegre tesisinde 'Demir İzabe' tesisi kurulması planlanmış ve yatırım faaliyetine geçilmiştir (Şekil 7).



Şekil 6: Altın Üretimi



Şekil 7: Demir Üretimi (Tesis Aşamasında)

5. Sonuçlar

Eti Bakır Küre işletmesinde bugüne kadar bakır konsanresi dışında herhangi bir hammadde üretilmezken, diğer bir ifadeyle kobalt, kükürt, flotasyonda kazanılamayan bakır ile altın ve gümüş gibi değerler; tesiste pirit flotasyonu yapılmak suretiyle bu konsantreye alınmakta ve atık barajında bırakılmamaktadır. Yine geliştirilen çok önemli bir proje ile Mazıdağı'nda kurulmuş olan ETİ Gübre Ve Metal Geri Kazanım Entegre Tesislerinde işlenmektedir;

1. Küre pirit konsanresi kavru olarak oluşan gazdan sülfürik asit üretilmektedir.
2. Sülfürik asit ile fosfat konsanresi reaksiyona sokularak, gübre üretiminde kullanılmak üzere fosforik asit üretilmektedir.
3. Kavurma sonrası elde edilen kalsin, basınç altında yükseltgeyici ortamda liç edilerek kalsinde bulunan Cu Co ve Zn çözündürülmektedir.
4. Çözündürülen bu elementler Türkiye'de ilk defa uygulanan Solvent Ekstraksiyon Tekniği ile kazanılmaktadır.
5. Altın gümüş otoklav sonrası elde edilen kekten siyanürleme işlemi ile kazanılmaktadır.
6. İşlemler sonrası geri kalan demiri yüksek atık ise, demir üretimine uygun bir hammaddedir. Tesis kurulmaktadır.

Sonuç olarak, Küre cevherinden elde edilen pirit konsanresi içerdiği kıymetli elementleri kazanılmak suretiyle Eti Gübre Mazıdağı Kompleksinde, herhangi bir atık ürün açığa çıkmadan değerlendirilmektedir. Bu tesis, sıfır atık prensibiyle çalışan örnek bir yatırımdır.

Teşekkür

Uzun yıllardır bilinmesine rağmen değerlendirilme şansı bulamamış olan kobalt entegre bir tesiste başarı ile gerçekleştirilmiştir. Bu tesisin kurulması aşamasında projelendirilmesinde ve faaliyete hazırlanmasında emeği geçen her çalışan, ben de dahil, teşekkürü hak etmiştir. Mazıdağı entegre tesisinin kurulmasında en büyük destekçisi Eti Bakır AŞ olup, burada işverenler Cengiz Holding sahipleri de teşekkürü hak etmektedirler. Ülkemizin yeni sıfır atık tesislerine kavuşması dileklerimle.

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- Seyrankaya ???



Risk-Based Inventory of Mine Waste Sites in Türkiye within the Scope of the EU Mine Waste Directive: Outcomes of the IPA Project (2012-2014)

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Özet

The EU Directive on the Management of Waste from the Extractive Industries (Directive 2006/21/EC, Mine Waste Directive (MWD)) requires the risk-based inventory of all mine waste sites in Europe by 2012. In this context, the present study provides a summary of the work carried out in the scope of the EU financed Mining Waste Management Project to prepare a risk-based inventory of closed and abandoned mine waste sites in Türkiye. In order to address the mining environmental problems a two-tiered approach based on the EU MWD Pre-selection Protocol was used in preparing a risk-based inventory. Potential mine waste sites were identified through a review of archival records of relevant intuitions, as well as an examination of scientific and technical publications and aerial photographs. After screening and preselection of mining sites (Tier 0 risk assessment), 300 sites were selected for Tier 1 risk assessment. Tier 1 risk assessment was carried out based on an 18- question survey organized into four sections- known significant impact and the source, pathway and receptor sections- using data both from existing databases and field surveys. The collected data were evaluated using a simple scoring system, with each site assigned a score between 1 and 14; uncertain responses were treated as "Yes" under the precautionary principle, except in section 1 (known significant impact).

The result indicated that, for most sites, the number of questions that could be reliably answered was seven or fewer, which is insufficient for an 18-questions risk assessment. Among the investigated waste sites, 15 were classified as posing no risk due to the incomplete source-pathway-receptor chain (i.e., the absence of one or more of the source, pathway, or receptor components). Based on the established threshold values, a total of 204 mine waste facilities with high-risk scores were identified as requiring "Further Examination". Of these facilities, 91 abandoned (88 waste rock piles, 3 tailings ponds/dams) and 113 are active (72 waste rock piles, 41 tailings ponds/dams).

Keywords; Mine Waste directive, risk-based inventory, Pre-selection protocol

1. Giriş

Abandoned mines and improperly closed mines are a significant problem in areas with long historic mining countries, because mining industry have evolved to become sustainable and responsible only in last 60 years. Apart from that abandoned mines are the same as active mines in terms of types of hazard and potential impact on the environment, their major problems are uncertainty in information and lack of control. Direct exposure to the acid mine drainage (AMD) and sediments discharged from abandoned metal mines poses a serious hazard to aquatic biota and to humans (Panagopoulos et al. 2009; Sarmiento et al. 2011). There are an estimated 3 million potentially contaminated sites in the whole European Union, of which about 250,000 are actually contaminated and in need of remediation (EEA, 2007).

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As part of Türkiye's integration process into the European Union (EU), the transposition of the EU Directive on mining waste into national legislation has become inevitable. To this end, the "Mining Waste Management" project, supported under the Instrument for Pre-Accession Assistance (IPA) Component I during the 2008 programming period, covered the harmonization of the relevant directive with national legislation, the enhancement of technical capacity, and the development of a risk-based inventory of mining waste sites in Türkiye.

This study presents the methodology and outcomes of the risk-based inventory developed between 2012 and 2014. The Turkish case encompasses not only abandoned mining waste facilities, as required by the directive, but also selected active mining waste sites.

1.1. Directive 2006/21/EC (Article 20)-risk-based inventory of abandoned mine waste sites

The EU Directive on the Management of Waste from the Extractive Industries (Directive 2006/21/EC, Mine Waste Directive (MWD)) requires in Article 20 that Member States shall ensure that an inventory of closed waste facilities, including abandoned waste facilities should be accomplished by 2012 and to update the inventory periodically thereafter. Article 21 further states that the inventory should be prepared on a risk-based approach.

Based on Article 20, the methodology to be used should possess the following characteristics: 1) be risk-based, i.e. consider both the probability of an event occurring and the impact of such an occurrence, 2) address the source, pathway and receptor paradigm, 3) be simple and office-based, 4) use readily available data, 5) address data and information uncertainty, 6) address serious damage to both human health and the environment (ecosystem) receptors, 7) assess whether the closed waste site contains either hazardous waste or dangerous substances, 8) assess the physical stability of the closed waste site, 9) address serious damage occurring at the present and the potential for such damage to occur into the future (medium term, i.e. 1 to 10 years), 10) provide a selection of waste sites for further assessment, 11) produce a selection of waste facilities that would be reasonably certain of capturing all relevant facilities, i.e. precautionary, 12) be reasonable and proportionate for the task (Abdaal et al, 2013).

1.2 Risk assessment (RA)

Contamination Risk assessment (RA) is defined as the probability of adverse effects to humans and ecosystem resulting from exposure to environmental pollutants (CARACAS 1999; US EPA 1989; 1998), therefore RA is concerned with the risk involved at a specific site, at a specific time, and due to specific causes. RA includes the steps of 1) hazard description, 2) dose/response (toxicity) analysis, 3) contaminant transport, 4) exposure assessment, 5) risk characterization, and 6) risk management (Van Leuwen and Hermens 1996; U.S. EPA 2002; 2007). Contamination risk exists for a site only if all the source, pathway and receptor components are present. In the case of mine waste sites, for example, this means that a hazardous waste should be present such as an ore tailings pond, contamination transport should be enabled by air, surface- and groundwater or direct contact to reach sensitive receptors such as settlements, protected ecosystems or agricultural lands.

2 Materials and Methods

Risk assessment was conducted using a two-tiered approach based on the EU MWD Pre-selection Protocol (Stanley et al. 2011; Abdaal, Jordan and Szilassi, 2013), comprising Tier 0 risk assessment (screening and pre-selection) and Tier 1 risk assessment (ranking and selection). Potential mine waste sites were identified through a review of archival records of relevant intuitions, as well as an examination of scientific and technical publications and aerial photographs. A total of approximately 500 potential mining sites were identified using multiple data sources. Tier 0 assessment, conducted using archival data, involved risk ranking of sites based on criteria such as commodity type, spatial distribution, evidence of acid mine drainage (AMD), facility size, proximity and type of environmental receptors, site abandonment status, and host geology. A mathematical model based on a risk rating approach was applied to evaluate the environmental risk associated with each site. Sites with confirmed evidence of Acid Mine Drainage (AMD) were directly classified as high-risk and included in the priority list without further scoring. Each parameter was assigned a score, and cumulative scores were calculated to determine overall risk levels. Based on the

scoring and ranking process, all together 300 sites were prioritized and ordered from highest to lowest risk for detailed assessment.

In the second stage, Tier 1 risk assessment was carried out based on an 18- question survey organized into four sections was carried out based on EU MWD Pre-selection Protocol (Stanley et al. 2011). The selected 300 sites were organized into 28 polygons, and field visits were conducted to collect the required data and information. During these visits, metallic, coal(lignite) and boron mine wastes were prioritized for sampling while inert mining waste, according to the Turkish Inert Mining Waste List, were generally excluded.

The EU MWD Pre-selection Protocol, as shown in Fig. 1, consists of four sections: (1) Known serious impact, (2) Source, (3) Pathways and (4) Receptors. Section 1 seeks to determine if a site has had a documented incident with a serious impact on human health or the environment (Q1). Section 2 addresses the chemical composition and physical stability of the mine waste site acting as potential contamination source (source questions Q2–Q10). Three questions address the content of the waste site, if the waste contains sulfide minerals (Q2), heavy metals (Q3) or the mine uses dangerous chemicals (Q4). This is followed by six questions that address the stability of the facility (see flowchart). Q5 asks if the type of the facility is either a tailings lagoon or a waste heap. If the site is a tailings lagoon, there are two further questions: if the area of tailings lagoon site is $>10.000\text{ m}^2$ (Q6) and the height is $>4\text{ m}$ (Q7). If the site is a waste rock heap, there are three further questions: if the waste heap area is $>10.000\text{ m}^2$ (Q7), the height is $>20\text{ m}$ (Q8) and the topographic slope under the waste heap site is $\geq 5^\circ$ (Q10). Section 3 considers the potential pathways by which receptors could be impacted by the mine waste source. Four pathway questions cover the four potential contamination transport routes: if a surface water course is within 1 km of a mine waste site (Q11), if there is a high permeability layer beneath the mine waste site (groundwater pathway; Q12), if the waste material is exposed to air (Q13) and if the waste site is uncovered allowing direct contact (Q14). Section 4 seeks to identify four major sensitive human and ecosystem receptors. Question Q15 examines if a human settlement with >100 people is located within 1 km of a waste site, Q16 asks if the waste site is located within 1 km distance of groundwater body in ‘poor status’, Q17 asks if a Natura 2000 site is located within 1 km distance of a waste site and Q18 inquires if a waste site is within 1 km distance of an agricultural area.

Tier 1 risk assessment is based on counting the “Yes” responses for each section at each site. The collected data from existing databases and field surveys were evaluated using a simple scoring system, with each site assigned a score between 1 and 14; uncertain responses were treated as “Yes” under the precautionary principle, except in section 1(known significant impact). This risk-based ranking and selection should result in the elimination of those sites which do not cause or have the potential to cause a serious threat to human health and the environment from the inventory of closed waste sites. Note that even if a waste facility passes the pre-selection protocol and classified as EXAMINE FURTHER, it does not mean that the abandoned/closed waste facility will necessarily be included in the final inventory.

2.1. The logic of the pre-selection protocol

The logic of the pre-selection protocol is designed to answer the target single yes-or-no question: should the closed waste facility be FURTHER EXAMINED? Or the question formulated as a Boolean true-false (yes-no) statement: The site should be further examined. According to the Mine Waste Directive this means that the ‘facility poses the risk of serious environmental impact’. Dictated by rules of formal mathematical logic, the pre-selection procedure has to be designed to provide an unambiguous conclusion to decide if this statement is TRUE or FALSE. In this pre-selection procedure, these two logic values are expressed as ‘YES’ or ‘NO’ answers to the target question, respectively. Further examination is required if and only if the facility pose risk at human health or the environment. A facility poses risk only if all the three risk components are present that is if there is a contamination source, a pathway for contamination transport and a sensitive receptor. The lack of any of these three components zeros out environmental risk. Therefore, there is a Boolean AND logical link between the Source, Pathway and Receptor compartments (Jordan and Selba, 2014)

Risk Assessment S-P-R		PARAMETER	VALUE	
1. IMPACT		Q 1. Is the closed mine waste facility known to have had an incident which has had a serious impact on human health or the environment?	YES/NO/UNKOWN	
2. SOURCE	2A. contents	Q 2. Did the mine work sulphide minerals or produce a waste containing sulphide minerals?	YES/NO/UNKOWN	
		Q 3. Were any of the following produced from the mined mineral - Ag, As, Ba, Be, Cd, Co, Cr, Cu, Hg, Ni, Pb, Sb, Se, Sn, Te, Tl, U, V, Zn or asbestos?	YES/NO/UNKOWN	
		Q 4. Did the mine use dangerous chemicals to process the mined minerals?	YES/NO/UNKOWN	
		Q 5. Is the waste facility a tailings lagoon or a waste heap?	YES/NO	
	2B. stability	Tailings	Q 6. Is the area of the tailings lagoon >10,000m ² ?	YES/NO/UNKOWN
			Q 7. Is the height of the tailings lagoon >4m?	YES/NO/UNKOWN
			Q 10. Is the slope of the foundation >1:12?	YES/NO/UNKOWN
		Waste heap	Q 8. Is the area of the waste heap >10,000m ² ?	YES/NO/UNKOWN
			Q 9. Is the height of the waste heap >20m?	YES/NO/UNKOWN
			Q 10. Is the slope of the foundation >1:12?	YES/NO/UNKOWN
3. PATHWAY		Q 11. SURFACE WATER Is there a water course within 1km of the mine waste facility?	YES/NO/UNKOWN	
		Q 12. GROUNDWATER Is there a high permeability layer beneath the mine waste facility?	YES/NO/UNKOWN	
		Q 13. AIR Is the material within the mine waste facility exposed to the wind?	YES/NO/UNKOWN	
		Q 14. DIRECT CONTACT Is direct contact possible?	YES/NO/UNKOWN	
4. RECEPTOR		Q 15. Is there a human settlement with >100 people within 1km of the waste facility?	YES/NO/UNKOWN	
		Q 16. Is the facility located within 1km of a water body (surface water resource or an aquifer)?	YES/NO/UNKOWN	
		Q 17. Is there a protected area within 1km of the waste facility?	YES/NO/UNKOWN	
		Q 18. Is the waste facility within 1km of agricultural land or livestock?	YES/NO/UNKOWN	

Figure 1: The questionnaire based on the EU MWD Pre-selection Protocol

3. Results and Discussion

The EU MWD Pre-selection Protocol provides a systematic approach for pre-screening and ranking contamination risks at mine waste sites, serving as a critical tool in early-stage decision-making. Its implementation typically relies on extensive GIS-based desk assessments. In contrast, data availability in Türkiye during the study period was highly limited. Essential digital spatial datasets—such as topographic maps, high-resolution (≤ 50 m) terrain data, and water body status—were scarce or inaccessible. As a result, Tier 1 risk assessments in Türkiye had to rely almost entirely on field data rather than the desk-based inventories commonly used in EU countries.

During field visits to the 300 identified sites, several limitations were encountered. These included locations where no mining activity actually existed, sites where mining operations were present but access was restricted (e.g., due to lack of transportation), and active mines where entry was denied by the operator. Additionally, some sites were found to have no mine waste storage facilities.

As pre-screening RA based on the EU MWD Pre-selection Protocol plays a key role in the first stage decision-making, however within the 300 sites, a considerable number of mining areas had seven or fewer questions answered, which was insufficient for the risk assessment study consisting of 18 questions. More interesting is that 60% of active mines had no information about the permeability of layers beneath their waste facilities to be provided at the time of the site visits. There were numerous active mines with basic information deficient about the geological conditions of their own sites in Turkey. It is noted that the obtained final ranking is sensitive to uncertainty because the precautionary principle renders high risk to unknown data. Every new piece of information would decrease the number of unknown parameter values and hence increase certainty and confidence that may change the risk ranking of facilities.

The hence developed RA inventory database contains 168 mine sites with about an equal number of Active (79 mines) and Abandoned (89 mines) sites. 36 sites have both tailings lagoon and waste rock heap inventoried yielding a total of 204 waste facilities consisting of 44 Tailings lagoons 160 Waste rock heaps. There are 91 Abandoned waste facilities (88 Waste rock heaps and 3 Tailings Lagoons) and 113 Active waste facilities (72 Waste rock heaps and 41 Tailing Lagoons) to be risk-assessed. The results showed that there are about 4 times more waste rock heaps than tailings lagoons in the metal, coal (lignite) and boron mining sector It is noteworthy that only three abandoned tailings lagoons were identified.

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Macun Dolgu Teknolojisinde Mermer Atığı Kullanımının Mekanik ve Mikroyapı Performansına Etkisi

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Özet

Mevcut araştırma, sülfürlü maden atığı (S-MA) yerine belirli oranlarda (%5-10-15) mermer atığı (MA) ikamesinin ÇMD'nin dayanım, duraylılık ve mikroyapı özelliklerine etkisi üzerine yoğunlaşmıştır. Bu amaç doğrultusunda, %8,5 çimento dozajında kontrol (%100 S-MA) ve S-MA yerine kısmen (%5-15) MA ikameli ÇMD numuneleri hazırlanmıştır. Numuneler üzerinde 7-28-90-180-360 gün boyunca basınç dayanımı (BD), pH (asit) ve SO_4^{2-} (sülfat) analizleri yürütülmüştür. Ayrıca, 28 günlük ÇMD'lere MIP cihazı vasıtasıyla porozite testleri uygulanmıştır. Bulgular değerlendirildiğinde, Kontrol ile karşılaştırıldığında, özellikle %15 MA içeren ÇMD numunelerinin dayanım ve duraylılık (dayanım kaybı) performansını geliştirdiği ve dolgu bünyesinde S-MA'da bulunan pirit mineralinin oksidasyonu sonucu üretilen asit ve sülfata karşı direnç gösterdiği belirlenmiştir. Porozite bulguları incelendiğinde ise, her iki ikame oranında (%5 ve %15) hazırlanan numunelerin kontrole nazaran daha düşük porozite ürettiği ve porozite bulgularının dayanım ve duraylılık bulgularını desteklediği belirlenmiştir. Sonuç olarak, ÇMD'nin baskın bileşeni olan S-MA'nın MA ile kısmen (%15) yer değiştirilmesinin mekanik ve mikroyapı performansı üzerinde olumlu etkisi olduğu anlaşılmıştır.

Anahtar Kelimeler; Macun dolgu, Sülfürlü maden atığı, Mermer atığı, Basınç dayanımı, Asit-sülfat, Porozite.

Influence of Marble Waste Utilization on the Mechanical and Microstructural Performances in Paste Backfill Technology

Abstract

The present study concentrates on the influence of marble waste (MW) substitution at different ratios (5-10-15%) for sulphidic mine tailings (S-MT) on the strength, durability, and microstructural characteristics of CPB. To this end, CPB mixtures were fabricated with a cement dosage of 8.5%, including a control mixture (100% S-MT) and mixtures in which S-MT was partially replaced by MW (5-15%). The CPB samples (CPBs) were put to compressive strength (UCS), acidity (pH), and sulfate (SO_4^{2-}) analyses over 7-28-90-180-360 days. Additionally, porosity measurements were conducted using MIP apparatus after 28 days. When the findings were appraised, it was designated that, compared to the control, CPBs containing 15% MW enhanced strength and durability (strength loss) performance, and exhibited resistance to the acid/sulfate produced by the pyrite mineral's oxidation in the S-MT, the dominant component of CPB matrix. Porosity analysis demonstrated that CPBs prepared with both 5% and 15% substitution ratios exhibited lower porosity values than the control, and the porosity findings supported the observed strength and durability results. Overall, the findings indicate that the partial substitution (15%) of S-MT-the dominant component of CPB-with MA has a favorable impact on the mechanical and microstructural performance of CPB.

Keywords; Paste backfill, Sulphidic mine tailings, Marble waste, Unconfined strength, Acid-sulphate, Porosity.

1. Giriş

Yeraltı maden işletmelerinde, arakatlı kazı ve kes doldur gibi üretim yöntemlerinde cevheri alınmış üretim odalarının tahkimat amacıyla cevher zenginleştirme sonucunda ortaya çıkan maden atıklarının depolanmasına imkan veren çimentolu macun dolgu (ÇMD), filtrasyon işlemine tabi tutulmuş zenginleştirme tesisi atıklarının (%75–85, ağırlıkça), nispeten düşük oranlarda kullanılan bağlayıcı malzeme (%2–9) ve su ile karıştırılması sonucu elde edilen yoğun ve homojen bir dolgu materyalidir. Bu kompozit yapı, karışım içerisinde ayrışma eğilimi göstermemesiyle karakterize edilmektedir (Li & Fall, 2018; Panchal vd., 2018; Yılmaz vd., 2018). ÇMD teknolojisi sayesinde zararlı mineraller barındırma potansiyeli bulunan maden atıklarının yaklaşık %50–55’lik bölümü yeraltı madenciliği sırasında oluşan açıklıklarda depolanabilmekte ve böylece yüzeyde kurulması gereken atık depolama tesislerine olan ihtiyaç azalmakta ve buna bağlı rehabilitasyon ile bakım maliyetleri önemli ölçüde düşürülebilmektedir (Pokharel & Fall, 2013; Yılmaz & Erçikdi, 2022a). Maden atıklarının çevre dostu bir biçimde ele alınmasına imkan vererek Avrupa Birliği nezdinde atık yönetimi konusunda en faydalı uygulamalardan birisi olarak gösterilen mevcut yöntem madencilik faaliyetlerinin uzun vadeli ve sürdürülebilir gelişimi hususunda önemli derecede rol oynamaktadır (European Commission, 2018; He vd., 2025).

Atık yönetimi açısından çevre dostu bir politika üstlenen ÇMD’nin tahkimat görevini yerine getirebilmesi için kısa dönemde gerekli olan dayanımı üretmesi ve uzun dönemde bu dayanımın devamlılık göstermesi oldukça büyük önem arz etmektedir. Bu hususta yaklaşık 40 yıllık bir geçmişe sahip olan ÇMD uygulamalarında sıklıkla kullanılan bağlayıcı malzemenin Portland çimentosu (PÇ) olduğu geçmiş çalışmalardan rahatlıkla anlaşılmaktadır (Yılmaz & Erçikdi, 2022b). Fakat, PÇ’nin maden atıkları bünyesinde bulunması muhtemel sülfür minerallerinin (pirit gibi) oksidatif reaksiyonları sonucu gelişen asit ve sülfat oluşumuna karşı koyma konusunda yeterli düzeyde direnç gösteremediği literatürde yer alan birçok çalışmada vurgulanmaktadır (Ercikdi vd., 2015; Yin vd., 2018; Yılmaz, 2019). ÇMD bünyesinde meydana gelen asit/sülfat oluşumuna karşı mücadelede PÇ’nin zayıf kalmasından dolayı, daha çok uzun dönemde dolgu matriksinde genleşme karakteristiğine sahip ikincil mineraller yüzünden oluşan çatlak vb. kusurlar dolgunun duraylılığını kaybetmesine (dayanım kaybı) sebep olmaktadır (Ercikdi vd., 2015). Bunun önüne geçilebilmek için ilk akla gelen alternatif bir çözüm olarak çimento miktarının artırılması ÇMD performansını geliştirse bile problemi tamamen çözememekte, dahası hem çimento sarfiyatında yaşanan artış yüzünden işletme maliyetleri olumsuz etkilenmekte hem de çimentoya olan talebin artması sonucu çimento üretim süreçlerinde yaşanan CO₂ emisyonları artışı hava kirliliğine ve atmosferin ısınmasına yol açmaktadır (Zheng vd., 2018; Yin vd., 2018; Erçikdi & Yılmaz, 2019).

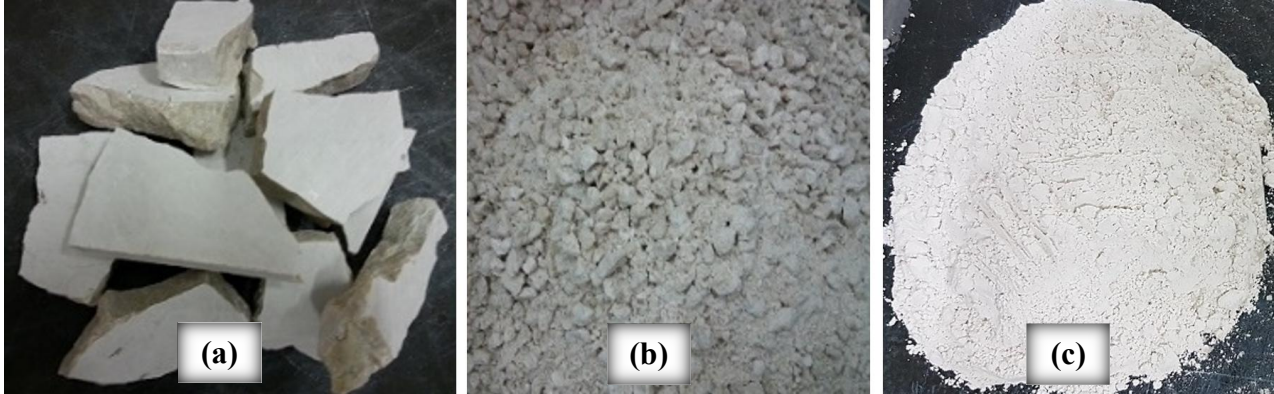
ÇMD ile ilgili hem yukarıda vurgulanan problemlerin çözümüne hem de ÇMD performansının geliştirilmesi amacıyla özellikle CaO içeriği yüksek katkı malzemelerinin çimento veya atık yerine ilave veya ikame edilerek kullanımına yönelik sayısız araştırmalar yürütülmüştür (Fall vd., 2007; Ercikdi vd., 2015; Yılmaz vd., 2017; Cihangir & Akyol, 2018; Li & Fall, 2018; Başçetin & Eker, 2019; Yılmaz vd., 2018; Yılmaz vd., 2020; Yılmaz vd., 2021; Yılmaz & Ercikdi, 2022a,b). Bu malzemelerden birisi olan mermer atığı (MA); bünyesinde çok yüksek oranda (%98’e kadar) kalsiyum karbonat (CaCO₃) barındıran ve metamorfik kayaç kategorisinde yer alan mermerin endüstriyel ölçekte bloklar halinde üretilmesi ve işlenmesi (kesme, boyutlandırma, şekil verme, vb.) sürecinde açığa çıkan inert karakterli bir yan üründür. Global mermer rezervinin (15 milyar m³) yaklaşık %30’unun ülkemizde (5,2 milyar m³) olduğu ve ülkemizdeki üretim ve işleme süreçleri esnasında yıllık 2,59 milyon ton MA ortaya çıktığı bildirilmiştir (Gesoglu vd., 2012; Alyamaç & Aydin, 2015; Kırgız, 2016). Bu atıkların uygun şekilde yönetilmemesi (depolanması, bertaraf edilmesi, vb.) çevresel açıdan ciddi riskler oluşturabilmektedir (Tozsın vd., 2014; Demir, 2017). Bu bağlamda, MA kullanılarak asfalt yol kaplamaları (Akbulut & Gürer, 2007), duraylılığı yüksek beton imali (Binici vd., 2008; Aliabdo vd., 2014; Sardinha vd., 2016), çimento üretimi (Aruntaş vd., 2010), tuğla yapımı (Bilgin vd., 2012), ÇMD karışım tasarımı (bağlayıcıya ikame olarak) (Ercikdi vd., 2015; Zheng vd., 2016) ve asit karakterli toprakların nötrleştirilmesi (Tozsın vd., 2014) gibi birçok farklı konuda çalışmalar yürütülmüştür.

Mevcut araştırma, daha önceki çalışmalardan farklı olarak sülfürlü maden atığı (S-MA) yerine belirli oranlarda (%5-10-15) mermer atığı (MA) ikamesinin %8,5 çimento dozajında imal edilen ÇMD’nin uzun dönem (360 güne kadar) dayanım, duraylılık ve mikroyapı özelliklerine etkisi üzerine yoğunlaşmıştır.

2. Materyal ve Metot

2.1. ÇMD Bileşenleri

ÇMD üretiminde baskın bileşen olarak yer alan sülfürlü maden atığı (S-MA) Kastamonu-Küre'deki Etibakır İşletmesi'nden, Portland çimentosu ise (PÇ: CEM I 42,5R) çalışma gerçekleştirildiği yıllarda Trabzon'da faaliyet gösteren Aşkale Çimento Fabrikası'ndan temin edilmiştir. ÇMD karışımlarında atık malzemeye ikame edilen mermer atığı (MA) Gümüşhane'deki mermer ocaklarından getirilmiştir. Ocaktan getirilmiş hali oldukça büyük boyutlu olan MA'nın S-MA ile benzer tane boyutu göstermesi adına MA üzerinde sırasıyla balyoz (Şekil 1a), çeneli kırıcı (Şekil 1b) ve bilyeli değirmen (Şekil 1c) yardımıyla boyut küçültme işlemleri yürütülmüştür.



Şekil 1. MA'nın kırma-öğütme sonrası görünümü: balyoz (a), çeneli kırıcı (b) ve bilyeli değirmen (c)

Bileşenlerin fiziksel karakterizasyon testleri (tane boyutu analizi (TBA): Malvern-Master Sizer 2000, özgül ağırlık (ÖA): 100 ml hacimli piknometre ve özgül yüzey alanı (ÖYA): AS-TEK blaine test cihazı) sonucunda edinilen bulgular Tablo 1'de sunulmuştur. Ayrıca, TBA sonucunda S-MA'nın %48,41 oranında ince (-20 µm) malzemeden oluştuğu görülmüştür.

Tablo 1. ÇMD bileşenlerinin fiziksel, kimyasal ve mineralojik özellikleri

Malzemeler	Fiziksel Özellikler				ÖA (g/cm ³)	ÖYA (cm ² /g)	Mineralojik Özellikler			
	Tane boyutu (µm)									
	D ₁₀	D ₃₀	D ₅₀	D ₈₀						
S-MA	2,0	8,0	22,0	68,5	3,37	4440	Pirit, Albit, Kuvars, Kalsit, Klorit			
PÇ	2,2	8,9	21,7	49,9	3,12	4330	C ₃ S =56,51	C ₃ A =8,79	C ₂ S =17,82	C ₄ AF =9,31
MA	1,2	5,0	14,8	51,0	2,70	4670	Kalsit			
Malzemeler	Kimyasal Özellikler									
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	S ⁻²	FeS ₂			
S-MA	31,89	8,97	33,09	4,08	3,48	15,82	29,66			
PÇ	21,02	5,27	3,06	2,19	62,91	-	-			
MA	1,09	0,48	0,09	0,16	55,74	-	-			

ICP AES ve XRD cihazları vasıtasıyla gerçekleştirilen kimyasal ve mineralojik karakterizasyon testleri, S-MA'nın esas olarak 3 mineralden (SiO₂, Al₂O₃ ve Fe₂O₃) oluştuğunu, bünyesinde pirit, kuvars, albit, klorit ve muskovit bulunduğunu ve %15,82 oranında sülfür içerdiğini göstermiştir. PÇ ve MA'nın ise sırasıyla %62,91

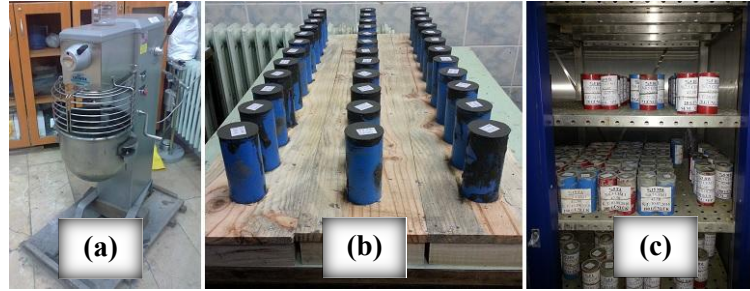
ve %55,74 oranında CaO minerali barındırdığı ve MA'nın çoğunlukla kalsit (CaCO_3) içerdiği gözlemlenmiştir (Tablo 1).

2.2. ÇMD Üretimi

ÇMD üretimi S-MA'nın 19,05 cm akışkanlığa bağlı katı oranı değerine uygun olarak 2 grupta (kontrol ve MA ikameli) gerçekleştirilmiştir. Kontrol (1.) grubu %8,5 PÇ dozajında tamamen (%100) S-MA içerirken, 2. grupta yer alan MA ikameli ÇMD'ler aynı bağlayıcı oranında S-MA yerine %5-10-15 oranında MA ikame edilerek üretilmiştir (Tablo 2). 1. grup (S-MA, PÇ ve musluk suyu) ve 2. grup (S-MA, PÇ, MA ve musluk suyu) ÇMD karışımları laboratuvar tipi karıştırıcı (Univex SRMF 20) 7 dakika boyunca ve 105 devir dönme hızında çalıştırılarak homojen bir biçimde hazırlanmıştır (Şekil 2a). Karışımlar alttan drenaj özellikli silindirik (5x10 cm) kalıplara doldurulmuş, fazla suyun drene olması için drenaj tablalarında 24 saat süresince bekletilmiş (Şekil 2b) ve ardından kür dolabında (sıcaklık: 20°C ve nem: %85) 7-360 gün süresince kürlenmiştir (Şekil 2c).

Tablo 2. ÇMD karışımlarına ait tasarım parametreleri

Karışım kodu	İkame oranı (%)		Bağlayıcı oranı (%)	Katı oranı (%)	Su/çimento oranı (%)	Akışkanlık (cm)
	S-MA	MA				
Kontrol	100	-		73,70	4,20	
%5 MA	95	5	8,5	73,97	4,14	19,05
%10 MA	90	10		74,33	4,06	
%15 MA	85	15		74,70	3,98	

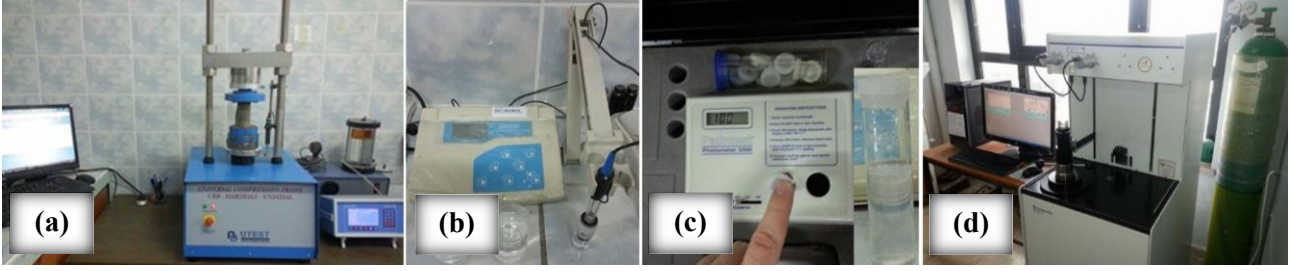


Şekil 2. ÇMD imalindeki karıştırıcı (a), numunelerin drenaj (b) ve kür süreci (c)

2.3. Uygulanan Testler/Analizler

Her kür süresi (7-28-90-180-360 gün) için 3 tane, toplamda ise 60 adet ÇMD numunesine uygulanan basınç dayanımı (BD) deneyleri, ASTM C39 (2016) standardı esas alınarak UTEST markası tarafından imal edilen basınç-deformasyon setinde (yükleme hızı= 1,00 mm/dk ve yük kapasitesi= 50 kN) gerçekleştirilmiştir (Şekil 3a).

BD testi tamamlanan ÇMD numuneleri 2,36 mm'lik elekten geçecek boyutta öğütülmüş, öğütülen numunelerden yaklaşık 1,25 g alınarak nem içerikleri (Sartorius MA35) belirlenmiş, buna bağlı olarak katı ve sıvı miktarları hesaplanarak katı-sıvı karışımları hazırlanmıştır. Hazırlanan karışımlar katı-sıvı ayrımının gerçekleşmesi amacıyla 1 saat ağızları kapalı bir biçimde bekletilmiş, ardından filtrasyon işlemi yapılarak elde edilen berrak sıvıların pH'ları (Oakton pH/Con 510) ölçülmüştür (Cihangir, 2011) (Şekil 3b).



Şekil 3. Uygulanan testler/analizler: BD testi (a), pH (b), sülfat (c) ve porozite (d) analizleri

Her karışımdan elde edilen berrak sıvılardan bir miktar cam tüplere alınmış ve saf su ile seyreltilerek içerisine sülfat analiz tableti ($BaCl_2$) eklenmiş ve plastik çubuk vasıtasıyla karıştırılmıştır. Sonrasında, cam tüpler Palintest photometer 5000 cihazındaki hazneye yerleştirilerek her bir ÇMD karışımının sülfat içeriği belirlenmiştir (Cihangir, 2011) (Şekil 3c).

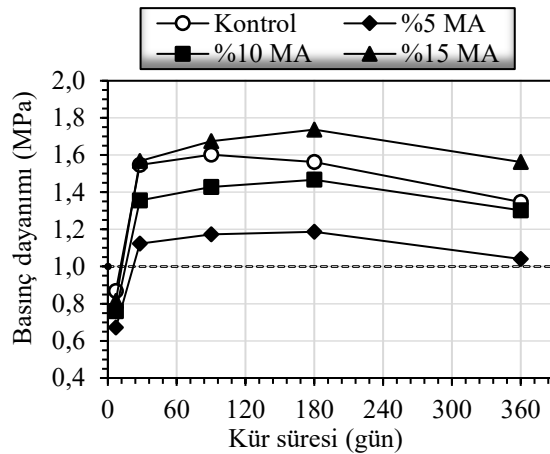
Yukarıda testleri/analizleri gerçekleştirilen ÇMD numuneleri ile aynı deneysel tasarım koşullarında üretilmiş 3 adet ÇMD numunesi (Kontrol, 5MA ve 15MA) 28 gün sonunda etüvde (sıcaklık= $50^{\circ}C$ ve süre= 60 saat) kurutulmuş, ardından desikatörde soğutulduktan sonra 3 cc'lik penetrometre içerisine sıgacak boyutta numune alınarak MIP cihazı (Micromeritics Autopore IV 9410) yardımıyla porozite analizleri yapılmıştır (ASTM D 4404-18, 2018) (Şekil 3d).

3. Bulgular ve Tartışma

3.1. Basınç Dayanımı Bulguları

Şekil 4, %8,5 çimento dozajında üretilen ÇMD (Kontrol ve %5-10-15 MA ikameli) numunelerinin 360 güne kadar gerçekleştirilen basınç dayanımı (BD) sonuçlarını içermektedir.

Kontrol ÇMD numuneleri 90 güne kadar dayanım kazanımı sağlarken, sonrasında düşüş eğilimine girmiştir. Buna karşın, S-MA yerine MA ikame edilerek imal edilen ÇMD numuneleri 180 güne kadar dayanım kazanımını sürdürmüş ve sonraki kür sürelerinde dayanım kaybı ortaya çıkmıştır. S-MA yerine MA ikamesinin etkisi incelendiğinde, ikame oranı artışının kür süresinden bağımsız olarak ÇMD'nin dayanım performansını geliştirdiği belirlenmiştir. Ayrıca, sadece %15 MA içeren macun dolgu numuneleri Kontrol'e kıyasla daha yüksek basınç dayanımı üretmiştir (Şekil 4). MA ikamesinin uzun dönem ÇMD performansı üzerindeki olumlu etkisi; S-MA'dan kaynaklanan oksidasyon sebebiyle oluşan asiti MA'nın nötralize etmesi ile açıklanabilir. Dahası, daha ince MA tanelerinin atık taneleri arasındaki boşlukları doldurarak karışımın katı oranını arttırması ($74,70 > 73,70$) ve su-çimento oranını azaltması ($3,98 < 4,20$) dayanım-duraylılık performansını geliştirmiştir (Tablo 2) (Ercikdi vd., 2013; Celik vd., 2014; Yılmaz vd., 2017).



Şekil 4. MA ikamesinin ÇMD'nin dayanım performansına etkisi

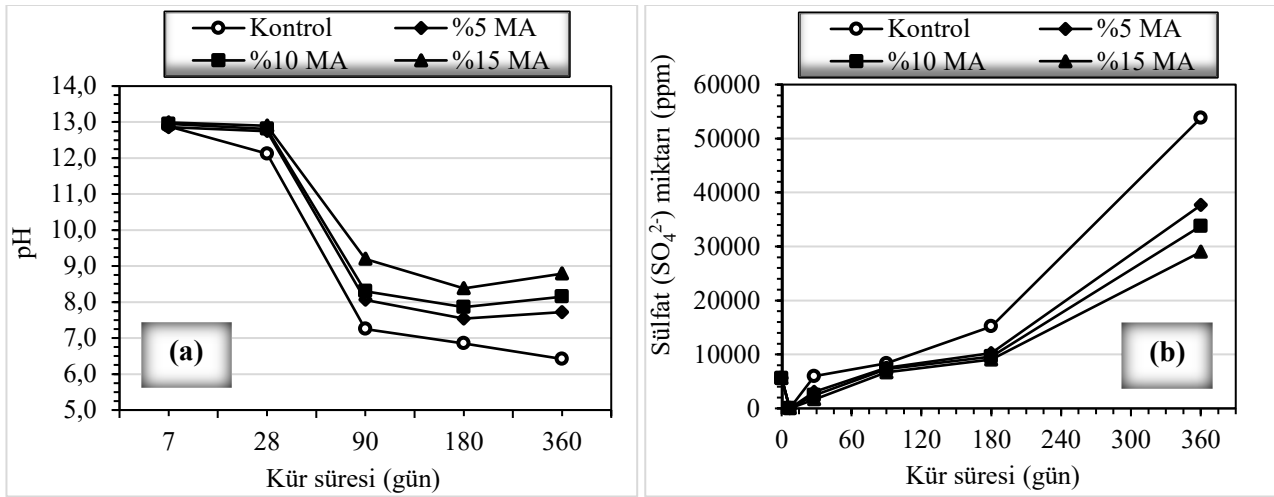
Asit ve sülfat kaynaklı uzun kür süresinde (>90 gün) ortaya çıkan dayanım düşüşü bulguları değerlendirildiğinde, kontrol numunelerinde %15,92 oranında dayanım kaybı oluşurken, MA ikameli ÇMD

numunelerinde %6,75-11,33 arasında kayıp meydana gelmiştir. Dayanım kaybı konusunda en dirençli numune; Kontrol ÇMD'ye kıyasla daha yüksek dayanım performansı gösteren %15 MA (%6,75) kodlu ÇMD numuneleri olmuştur (Şekil 4). Bunlara ek olarak, dayanım/duraylılık hususunda limit basınç dayanımı ($\geq 1,0$ MPa) (Yumlu, 2001) değerinin bütün ÇMD numuneleri tarafından sağlandığı saptanmıştır.

3.2. pH ve Sülfat Bulguları

%8,5 PÇ dozajında üretilen ÇMD (Kontrol ve %5-10-15 MA ikameli) numunelerinin 7, 28, 90, 180 ve 360 gün sonunda yapılan pH ve sülfat ölçüm sonuçları sırasıyla Şekil 5 ve 6'da sunulmuştur.

Kısa dönemde (7 ve 28 gün) bütün ÇMD numunelerinin pH değerlerinin bazik tarafta ($>12,0$) kaldığı belirlenmiştir. Bu durum, çimentonun hidrasyonu sürecinde kalsiyum hidroksit minerallerinin üretilerek ortamın bazik pH'da tutulmasıyla ilişkilendirilebilir (Cihangir vd., 2015; Yılmaz vd., 2018). 28-90 gün aralığında ise tüm numunelerden fitre edilerek elde edilen sulara pH'nın 7,25'lere kadar hızlı bir şekilde düştüğü gözlemlenmiştir. Bu hızlı düşüş kontrol numunelerinde devam ederek 360 gün sonunda pH nötral seviyenin altında (6,42) seyretmiştir. MA ikameli (%5-10-15) ÇMD numunelerinde ise asit oluşumu 90 günden sonra yavaşlaşsa da 180 güne kadar devam etmiş, ardından 360 güne doğru azalma eğilimi göstermiştir (Şekil 5a). Tüm numunelerde meydana gelen asit oluşumu, ÇMD'nin baskın bileşeni olan S-MA'da oksidasyon kaynaklı olarak pirit minerallerinin H^+ iyonu üretmesine bağlanabilir (Yılmaz, 2019). ÇMD bünyesinde MA ikame miktarının artması, ÇMD numunelerinin asit üretimini yavaşlatmış ve 360 gün sonunda özellikle %15 MA ikameli ÇMD'de Kontrol'e kıyasla oldukça yüksek pH değeri ($8,79 > 6,42$) ölçülmüştür (Şekil 5a). MA'nın asit üretimine karşı gösterdiği direnç, asit nötrleştirme karakteristiği bulunan mermerdeki kalsit mineralinin çözünmesine ve böylece ortama OH^- iyonu salınımına bağlanabilir (Fernández-Caliani & Barba-Brioso, 2010; Ercikdi vd., 2015).



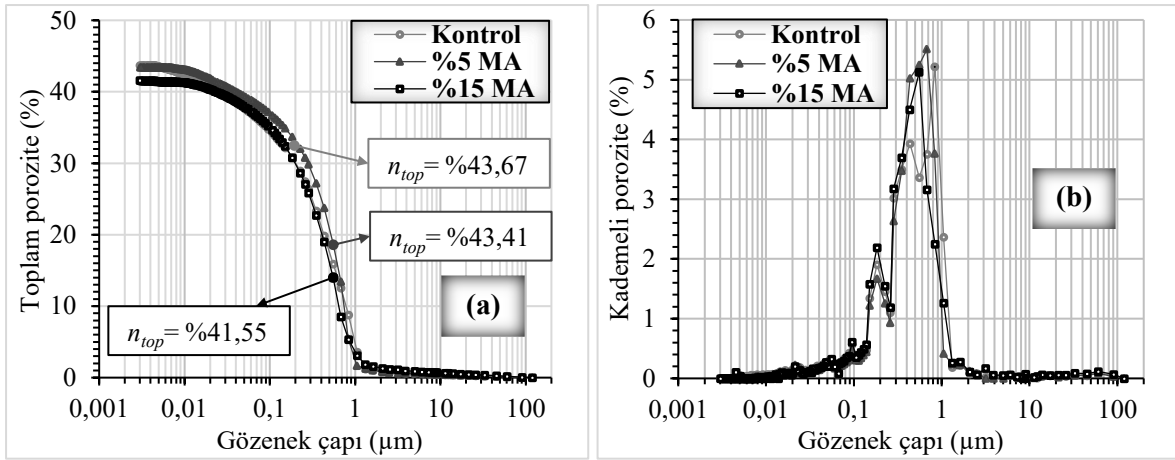
Şekil 5. MA ikamesinin ÇMD'nin pH (a) ve sülfat (b) oluşumuna etkisi

Şekil 5b'de gösterilmekte olan sülfat (SO_4^{2-}) içerikleri değerlendirildiğinde, S-MA bünyesinde var olan 5616 ppm sülfatın çimento hidrasyon bileşenleri tarafından jips ve etrenjit olarak bağlanması sonucunda tüm numunelerin 7 gün sonunda sülfat (SO_4^{2-}) içerikleri sıfır "0" çıkmıştır. Sonrasında, dolgu bünyesinde devam eden hidrasyon sürecinden dolayı 28-90 gün boyunca daha yavaş artan sülfat iyonu oluşumu 90-360 gün aralığında tüm numunelerde artarak devam etmiştir. Bu durum, oksidasyon sonucu asit ve sülfat oluşumuna sebep olan pirit minerali miktarının azalmasına bağlanabilir (Yılmaz, 2019). Tüm bunlara ek olarak, MA ikamesinin ÇMD bünyesinde oluşan sülfat iyonu miktarlarını azalttığı ve ikame oranı arttıkça sülfat oluşumunun azaldığı tespit edilmiştir. Kontrol numunesinde 360 gün sonunda 53790 ppm sülfat oluşurken, özellikle %15 MA içeren ÇMD'de Kontrol'e nazaran %46,1 düşüş oranıyla 28996 ppm sülfat iyonu üretilmiştir (Şekil 5b).

3.3. Porozite Bulguları

%8,5 PÇ dozajında üretilen Kontrol ve S-MA yerine %5-15 oranlarında MA ikamesiyle imal edilen ÇMD numunelerinin 28 gün sonunda MIP cihazı vasıtasıyla gerçekleştirilen porozite (toplam: n_{top} ve kademeli) değişimleri Şekil 6'da gösterilmiştir.

ÇMD numunelerinin 28 gün sonunda yapılan porozite analizlerinden toplam porozite (n_{top}) değerleri Kontrol, %5 MA ve %15 MA numuneleri için sırasıyla %43,67, %43,41 ve %41,55 olarak ölçülmüştür. MA ikamesinin numunelerin n_{top} değerlerinde azalma sağladığı ve Kontrol numunesi ile kıyaslandığında %5 ve %15 MA numunelerinde sırasıyla %0,6 ve %4,9 oranlarında daha düşük toplam porozite üretildiği tespit edilmiştir (Şekil 6a). Kademeli porozite bulguları ise, Kontrol, %5 MA ve %15 MA numuneleri için %5,21, %5,51 ve %5,12 olarak belirlenmiş ve %15 MA ikameli macun dolgu numunelerinin nispeten daha düşük kademeli porozite ürettiği saptanmıştır (Şekil 6b). Kontrol ÇMD numunesi ile karşılaştırıldığında, özellikle %15 MA ikamesinin ÇMD'nin porozite performansına yaptığı olumlu katkının sebebi olarak S-MA'ya nazaran daha küçük boyutlu tane içeren ve dolayısıyla daha büyük ÖYA değeri (Tablo 1) gösteren MA tanelerinin S-MA taneleri arasına girerek (filler etkisi) karışımın su ihtiyacını azaltması (yani daha düşük su-çimento oranı) ve katı içeriğini yükseltmesi (Tablo 2) gösterilebilir (Ercikdi vd., 2013; Celik vd., 2014; Yılmaz ve Ercikdi, 2016; Yılmaz vd., 2017; Yılmaz vd., 2018).



Şekil 6. MA ikamesinin ÇMD'nin 28 gündeki toplam (a) ve kademeli (b) porozite değişimlerine etkisi

4. Sonuçlar

Bu çalışmada, sülfürlü maden atığı (S-MA) içeren çimentolu macun dolgu (ÇMD) karışımlarında mermer atığının (MA) farklı oranlarda (%5, %10 ve %15) ikame edilmesinin uzun dönem dayanım, duraylılık (asit ve sülfat oluşumu) ve porozite performansı üzerindeki etkileri kapsamlı olarak araştırılmıştır. Bu amaç doğrultusunda 360 güne kadar kür edilen numuneler üzerinde basınç dayanımı, pH, sülfat oluşumu ve 28 günlük ÇMD'ler üzerinde porozite analizleri gerçekleştirilmiştir. Sonuçlar, MA kullanımının ÇMD performansını belirgin şekilde iyileştirdiğini göstermektedir. MA içeren karışımlarda dayanım gelişimi 180 güne kadar devam etmiş ve tüm kür sürelerinde özellikle %15 MA ikameli numunelerde, Kontrol'e kıyasla hem daha yüksek dayanım değerleri edinilmiş hem de en düşük uzun dönem dayanım kaybı (%6,75) sergilenerek en iyi performansı ortaya konmuştur. ÇMD bünyesinde artan MA oranı ile birlikte daha yüksek pH değerleri korunmuş ve 360 gün sonunda sülfat içeriğinde yaklaşık %46'ya varan azalma sağlanarak MA ikamesinin asit ve sülfat üretimini önemli ölçüde sınırlandırdığı belirlenmiştir. Dahası, porozite analizlerinden, ince taneli MA'nın boşluk doldurma etkisi sayesinde su-çimento oranında azalma ve katı oranında artış sağlanarak daha düşük toplam poroziteli daha yoğun bir yapı oluşumuna katkı sağlandığı gözlemlenmiştir.

Sonuç olarak, ÇMD karışımları içerisinde uygun miktarda mermer atığı (%15 MA) ikamesinin ÇMD'nin dayanım, duraylılık ve mikroyapı performansını artıran etkili ve sürdürülebilir bir katkı malzemesi olduğu ortaya konmuştur.

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Macun Dolgu Teknolojisinde Mermer Atığı Kullanımının Jeokimyasal Davranışa Etkisi: Tank Liçi Testi

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Özet

Bu araştırma, sülfürlü maden atıklarından (S-MA) üretilen çimentolu macun dolgunun (ÇMD), maden kapatma sonrası yeraltı sularıyla dolması senaryosundaki uzun vadeli jeokimyasal davranışını değerlendirmeyi amaçlamaktadır. Bu kapsamda, sadece S-MA kullanılarak kontrol numuneleri ve S-MA yerine ağırlıkça %10 oranında mermer atığı (MA) kullanılarak %8,5 bağlayıcı oranında ÇMD numuneleri üretilmiştir. Numunelere 30-360 gün boyunca dinamik tank liçi testi uygulanmış ve filtrasyon sonucu edinilen sular asit (pH), sülfat ve elektrik iletkenliği (EC) testlerine tabi tutulmuştur. Ayrıca, mikroyapı özelliklerinin ÇMD'nin jeokimyasal davranışına etkisi porozite (MIP) testleri ile incelenmiştir. Bulgular, kontrol numunesinin 30-180 gün arasındaki liç süresi boyunca pH değerinin yükseldiğini, ardından 7,36'ya kadar düştüğünü göstermiştir. Buna karşın, %10 MA ikameli (10MA kodlu) ÇMD numunesinin pH değerinin 30-360 gün boyunca istikrarlı bir şekilde 8,35'e kadar arttığı belirlenmiştir. Ayrıca, 10MA genel olarak tüm liç sürelerinde Kontrol'e kıyasla daha düşük iletkenlik göstermiştir. %10 MA ikamesi sülfat konsantrasyonunu %22,7'ye kadar azaltmıştır. ÇMD mikroyapısının etkisi değerlendirildiğinde, %10 MA ikamesinin poroziteyi (toplam/kademeli) azaltarak daha kompakt bir dolgu matrisi oluşturduğu ve bu sayede ÇMD'nin geçirgenliğini azalttığı ortaya çıkmıştır. Sonuç olarak, ÇMD karışımlarında mermer atığı kullanılarak hem ÇMD'nin S-MA'dan kaynaklanan kirlilik sızıntısı engellenmiş ve/veya azaltılmış olur hem de MA'nın çevreye duyarlı şekilde depolanması sağlanabilir.

Anahtar Kelimeler: Macun dolgu, Sülfürlü maden atığı, Mermer atığı, Jeokimyasal davranış, Tank liçi testi.

Effect of the utilization of Marble Waste in Paste Backfill Technology on Geochemical Behavior: Tank Leaching Test

Abstract

This study aims to evaluate the long-term geochemical behavior of cemented paste backfill (CPB) produced from sulfide mine tailings (S-MA) under a post-closure scenario in which underground workings become flooded with groundwater. Within this scope, control specimens were prepared using only S-MA, while CPB samples (CPBs) were produced by replacing 10 wt.% of S-MA with marble waste (MW) at 8.5% binder content. The CPBs were subjected to dynamic tank leaching (DTL) tests over 30–360 days, and the leachates obtained after filtration were analyzed for pH, sulfate, and electrical conductivity (EC). Furthermore, MIP-based porosity analysis assessed microstructural influences on CPB geochemistry. The findings indicated that the pH of the control increased during the leaching period between 30-180 days, followed by a decrease to 7.36. In contrast, the pH of CPB substituting 10% MA (10MA) steadily increased, reaching 8.35 throughout the 30–360 day. Besides, 10MA generally demonstrated lower EC than the control at all leaching periods. The substitution of 10% MW lowered the sulfate concentration of up to 22.7%. Microstructural analysis revealed that the incorporation of 10% MW reduced both total and incremental porosity, leading to the formation of a more compact backfill matrix and, consequently, lower permeability. Overall, the use of marble waste in CPB

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mixtures not only mitigates and/or prevents contaminant leaching associated with S-MA, but also enables the environmentally responsible management of marble waste.

Keywords; Paste backfill, Sulphidic mine tailings, Marble waste, Geochemical behaviour, Tank leaching test.

1. Giriş

Cu, Pb ve Zn vb. kıymetli metaller içeren metalik cevherlerin ince öğütme gerektiren yöntemler (flotasyon, vb.) vasıtasıyla zenginleştirilerek ekonomiye kazandırılması safhasında tane boyutu çoğunlukla <100 µm olan büyük hacimli sülfürlü maden atıkları (S-MA) ortaya çıkmaktadır (Yılmaz vd., 2020). Çevresel anlamda problem oluşturma potansiyeli taşıyan bu atıkların, kompozit bir mühendislik karışımı olan çimentolu macun dolgu (ÇMD) teknolojisi kullanılarak yeraltında emniyetli bir biçimde depolanabileceği ifade edilmiştir (European Commission, 2018; Li ve Fall, 2018; Yılmaz vd., 2018). Bu karışım; filtrasyon işlemi uygulanan tesis atığı (%75-85), dayanım kazanması için kullanılan çimento (%2-9) ve macun dolgu tesisinden yeraltında cevheri alınmış üretim odalarına rahatlıkla gönderilebilmesi için gereken sudan (%15-25) oluşmaktadır (Yılmaz vd., 2018). Hem atık yönetimi açısından etkin bir çözüm sunan hem de madencilik faaliyetlerinin uzun vadeli ve sürdürülebilir gelişimine katkıda bulunan bu yöntem; derin seviyelerde oluşan zemin basıncının kontrol altına alınmasından (Li vd., 2024) kaya tabakalarının stabilizasyonuna (Keskin vd., 2024), yüzey deformasyonlarının azaltılmasından (Guo vd., 2024) atık depolama alanlarının kapladığı geniş arazilerin sınırlandırılmasına (Hou vd., 2024) kadar çeşitli çözümler sunmaktadır (He vd., 2025).

Madencilik operasyonları süresince yüzey ve yeraltı kaynaklarından gelen, çeşitli kirleticiler içerebilen sular yeraltı madeninin taban kısmında toplanarak buradan dış ortama tahliye edilmektedir. Bundan dolayı yeraltı su seviyesi (YSS) yıllarca (maden kapanma sonrasına kadar) cevheri alınmış üretim odalarına yerleştirilen ÇMD kütlesinin altında seyredebilir (Yılmaz vd., 2021). Böylelikle atmosferik koşullara (hava ve nem) sahip olan ve bünyesinde sülfürlü mineraller (pirit vb.) barındıran ÇMD kütlesi oksidasyona elverişli davranarak yüksek konsantrasyonda asit üretimi ve ağır metal salınımı sergileyebilir. Cevher üretiminin ardından gerçekleştirilen ÇMD uygulamasını takiben özellikle uzun dönemde (>28 gün) ÇMD kütlesinde meydana gelen kirletici karakterli oksidasyon bileşenleri, yeraltı madenindeki üretim faaliyetlerinin sona ermesinde sonra YSS'nin yükselerek ÇMD kütlesinin üzerinde bir seviyeye ulaşmasıyla birlikte yeraltı suyunun kirlenmesine sebep olabilir (Hamberg vd., 2018; Bull ve Fall 2020; Yang vd., 2020; Yılmaz ve Ercikdi, 2022).

ÇMD'nin uygulamada yaygın bir biçimde kullanılmasıyla birlikte günümüze kadar çoğunlukla en kötü senaryo olan ÇMD'nin bütünlüğünü (duraylılığını) kaybetmesi sonucu ortaya çıkması muhtemel asit-sülfat oluşumunu araştıran çalışmalar yürütülmüştür (Cihangir vd., 2012; Ercikdi vd., 2013; Yılmaz vd., 2020; Kasap vd., 2022). Fakat, yeraltında cevheri alınmış üretim odalarına yerleştirilen ÇMD kütlesinin bütüncül (yekpare) halde ortaya koyacağı davranış basınç dayanımı kadar veya daha da önemli bir diğer kalite göstergesidir. Bundan dolayı ÇMD'nin çevresel davranışının araştırılmasında bütün (yekpare) ÇMD numunelerinden faydalanılmasının daha doğru bir yaklaşım olduğu bildirilmiştir (Jiao vd., 2011). Bundan dolayı, YSS'nin ÇMD kütlesinin üzerine yükselmesiyle ortaya çıkan durumda bütünlüğünü koruyan (monolitik) ÇMD'nin çevresel anlamda nasıl davranış göstereceğinin laboratuvar koşullarında dinamik tank liçi (DTL) testi vasıtasıyla irdelenmesine yönelik bazı çalışmalar yapılmıştır (Coussy vd., 2011; Jiao vd., 2011; Hamberg vd., 2015; Schafer, 2016; Hamberg vd., 2017; Seipel vd., 2017; Yılmaz vd., 2018; Yılmaz vd., 2021; Yılmaz ve Ercikdi, 2022). Bünyesinde arsenik (As) bulunan atıklarla üretilen ÇMD numuneleri üzerinde 64 günlük DTL testi uygulayarak As salınımını araştıran yazarlar, testlerde edinilen suların 10,4'ün üzerinde pH gösterdiğini ve bu pH değerlerinin As salınım hızını arttırdığını rapor etmişlerdir (Coussy vd., 2011). Küp şekilli ÇMD numuneleri imal ederek saf su içerisinde 75 güne kadar bekleten ve belirli periyotlarda kadmiyum (Cd), arsenik (As), çinko (Zn) ve kurşun (Pb) gibi ağır metallerin suya salınma değişimlerini inceleyen Jiao vd. (2011) yeraltı suyu kalitesi hususunda ağır metal salınım değerlerinin tehlike arz etmediğini bildirmişlerdir. Başka bir araştırmada, siyanür içeren tesis atığı ve bu atık ile üretilen ÇMD numunelerinin çevresel performansı DTL testleri yapılarak incelenmiştir. Araştırma bulguları, ÇMD numunelerinin atık malzemeye nazaran daha yüksek pH değerleri (7,9-10,4>3,9-6,0) sergilediklerini ve sülfür salınımının düşüş gösterdiğini ortaya çıkarmıştır (Hamberg vd., 2015). Ayrıca, yazarların daha sonraki yıllarda düşük dayanımlı ÇMD'nin çevresel davranışı üzerine gerçekleştirdikleri çalışmalarda ÇMD kütlesinde oluşması muhtemel oksidasyonun ve böylece ortaya çıkabilecek kirleticilerin engellenmesi ve/veya sınırlandırılması için YSS'nin kısa sürede ÇMD

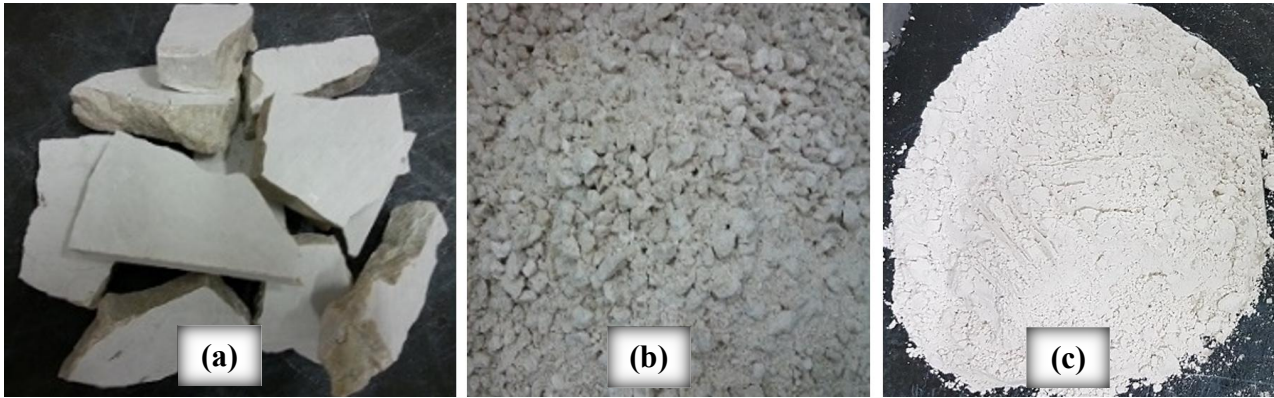
kütlesinin üzerine çıkması gerektiği vurgulanmıştır (Hamberg vd., 2017; Hamberg vd., 2018). Geçmişte sülfür içeriği düşük ($S^{2-} \leq \%2,0$) atık malzemelerden imal edilen ÇMD numuneleri üzerinde kısa süreli (≤ 75 gün) DTL testleri uygulanarak yürütülen araştırmaların aksine, $S^{2-} \cong \%16$ olan atık malzeme yerine farklı endüstriyel atık ürünler (cüruf, uçucu kül, bina atığı, kireçtaşı) ikame edilerek üretilen ÇMD'lerin 30-360 günlük DTL testleri sonucunda atık ürün içeren ÇMD numunelerinin daha alkali seviyelerde kaldığı, sülfat oluşumunu sınırladığı ve mikroyapı performansındaki gelişime paralel olarak ağır metallerin sızıntı suyuna geçişinin engellendiği/kısıtlandığı rapor edilmiştir (Yılmaz vd., 2021; Yılmaz ve Ercikdi, 2022; Yılmaz ve Ercikdi, 2022).

Bu deneysel çalışmada, yaklaşık $\%16 S^{2-}$ içeren sülfürlü maden atığı (S-MA) yerine ikame olarak mermerin blok üretimi ve işlenmesi süreçleri sırasında ortaya çıkan mermer atığının (MA) $\%10$ oranında kullanımının ÇMD'nin jeokimyasal performansına etkisi araştırılmıştır. Bu çerçevede, $\%8,5$ bağlayıcı dozajında tamamen S-MA kullanılarak (Kontrol) ve S-MA yerine $\%10$ oranında MA ikame edilerek ($\%10$ MA) ÇMD numuneleri imal edilmiştir. Bu numuneler 180 gün boyunca kürlendikten sonra numuneler üzerinde 6 farklı liç süresi (30-60-90-180-270-360 gün) boyunca dinamik tank liçi (DTL) testi uygulanmıştır. Her liç süresi sonunda filtrasyon ile elde edilen suların asit (pH), elektrik iletkenliği (EC) ve sülfat (SO_4^{2-}) ölçümleri yapılmıştır. Dahası, mikroyapı özelliklerinin ÇMD'nin jeokimyasal davranışına etkisi porozite (MIP) testleri ile incelenmiştir.

2. Deneysel Çalışmalar

2.1. ÇMD Bileşenleri

ÇMD üretiminde baskın bileşen olarak yer alan sülfürlü maden atığı (S-MA) Kastamonu-Küre'deki Etibakır İşletmesi'nden, Portland çimentosu ise (PÇ: CEM I 42,5R) çalışma gerçekleştirildiği yıllarda Trabzon'da faaliyet gösteren Aşkale Çimento Fabrikası'ndan temin edilmiştir. ÇMD karışımlarında atık malzemeye ikame edilen mermer atığı (MA) Gümüşhane'deki mermer ocaklarından getirilmiştir. Ocaktan getirilmiş hali oldukça büyük boyutlu olan MA'nın S-MA ile benzer tane boyutu göstermesi adına MA üzerinde sırasıyla balyoz (Şekil 1a), çeneli kırıcı (Şekil 1b) ve bilyeli değirmen (Şekil 1c) yardımıyla boyut küçültme işlemleri yürütülmüştür.

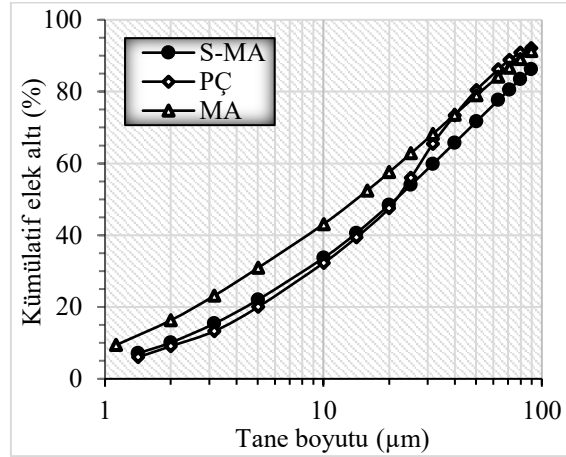


Şekil 1. MA'nın kırma-öğütme sonrası görünümü: balyoz (a), çeneli kırıcı (b) ve bilyeli değirmen (c)

Fiziksel karakterizasyon testleri kapsamında, ÇMD'yi oluşturan bileşenler üzerinde özgül ağırlık ($\text{ÖA} = \text{piknometre}$), tane boyutu dağılımı (TBD= Malvern-Master Sizer 2000) ve özgül yüzey alanı ($\text{ÖYA} = \text{AS-TEK blaine cihazı}$) analizleri yürütülmüştür. Malzemelerin TBD sonuçları Şekil 2'de verilmiş olup, S-MA'nın ince boyutlu ($-20 \mu\text{m}$) tane içeriği $\%48,4$ olarak ölçülmüştür. Ayrıca S-MA, PÇ ve MA'nın D_{80} tane boyutlarının sırasıyla $68,5 \mu\text{m}$, $49,9 \mu\text{m}$ ve $51,0 \mu\text{m}$ olduğu tespit edilmiştir (Şekil 2). ÖA bulguları, bileşenler (S-MA, PÇ ve MA) için sırasıyla $3,37$, $3,12$ ve $2,70 \text{ g/cm}^3$ olarak ölçülmüş iken, yapılan ölçümler sonucunda blaine cihazı 4440 , 4330 ve $4670 \text{ cm}^2/\text{g}$ 'lık ÖYA değerleri göstermiştir.

ÇMD bileşenlerinin kimyasal bileşimlerinin analiz edilmesinde ICP AES'ten yararlanılırken, mineralojik karakterizasyonu için XRD cihazı kullanılmıştır. Yürütülen analizler doğrultusunda, S-MA'nın içeriğinde baskın olarak demirli, silisli ve alüminli mineral fazlarının ($\text{Fe}_2\text{O}_3 = 33,09$, $\text{SiO}_2 = \%31,89$ ve $\text{Al}_2\text{O}_3 = 8,97$) yer

aldığı, bununla birlikte pirit (FeS_2) içeriğinin ve dolayısıyla sülfür (S^{2-}) miktarının sırasıyla %29,66 ve ~%16 olduğu saptanmıştır. Bağlayıcı (PÇ) ve MA'ya bakıldığında ise bileşenlerin yarısından fazlasının (sırasıyla %62,91 ve %55,74) kalsiyum oksit (CaO) içerdiği raporlanmıştır. Tüm bunlara ek olarak, S-MA mineralojik olarak pirit, albit, kuvars, kalsit ve klorit içerirken, MA'da kalsit (CaCO_3) minerali bulunmaktadır.



Şekil 2. ÇMD bileşenlerinin TBD ölçüm sonucu

2.2. Asit-baz hesaplama (A-BH) testi

Sobek vd. (1978) tarafından geliştirilen metot uyarınca yürütülen bu test kapsamında S-MA ve MA'nın ilk olarak fışırdaama kategorileri ve ardından asit ve nötrleştirme potansiyelleri (sırasıyla AP ve NP) hesaplanmıştır. Daha sonra, bu testlerin Yılmaz (2019) ve Yılmaz vd. (2021)'nin çalışmalarında oldukça detaylı bir biçimde açıklandığı üzere, malzemelerin sırasıyla nötrleştirme (NP) ve net nötrleştirme potansiyellerinin (NNP) tespiti için asit-baz titrasyon testi gerçekleştirilmiştir. İlgili bulguların hesaplanmasında aşağıda sunulan eşitliklerden faydalanılmış ve testlere ait sonuçlar Tablo 1'de gösterilmiştir. Eşitliklerde verilen A_n ve B_n : asit ve bazın normalitesi (N), A_h ve B_h : asit ve bazın hacmi (ml) iken, a: numune ağırlığı (g)'dir.

$$(1) AP = 31,25 \times S^{2-}$$

$$(2) NP = ((A_n \times A_h) - (B_n \times B_h)) / a$$

$$(3) NNP = NP - AP$$

Tablo 1. Bileşenlerin A-BH testi sonuçları

Özellikler	S-MA	MA	Özellikler	S-MA	MA
S^{2-} içeriği (%)	~%16	-	Asit hacmi (ml)	20	80
CaO içeriği (%)	3,48	55,74	AP*	494,4	0
Fışırdaama sınıfı	Yok	Sert	NP*	8,6	987,8
Asit normalitesi (N)	0,1	0,5	NNP*	-485,8	987,8

*: kg CaCO_3 /ton atık

2.2. ÇMD Üretim Süreci

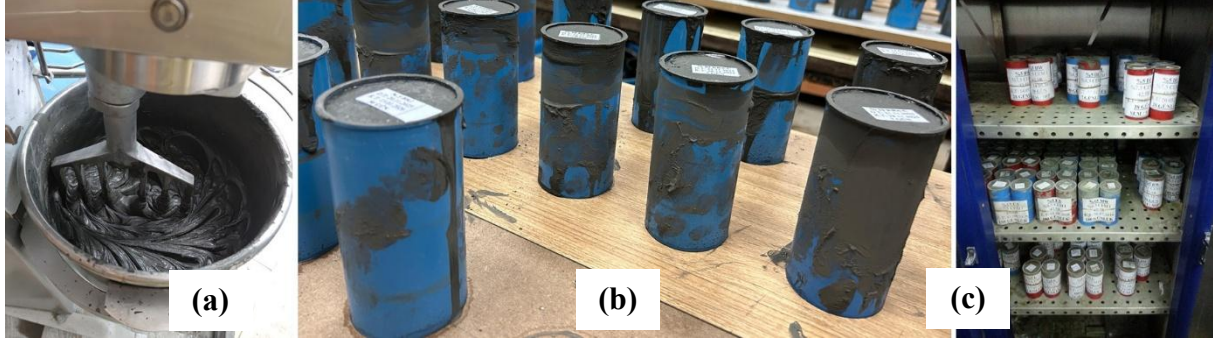
Tablo 2'de sunulan ÇMD numunelerinin üretimi sırasında faydalanılan karışım tasarım parametreleri uyarınca macun dolgu numuneleri için hazırlanan karışımlarda bağlayıcı dozajı %8,5 olarak belirlenirken, slamp konisi kullanılarak gerçekleştirilen akışkanlık testleri sonucunda karışımların 19,05 cm'lik akışkanlık (slamp) değerine göre imal edilmesi kararlaştırılmıştır. Kontrol numunelerinin yalnızca S-MA (%100) kullanılarak imal edildiği ÇMD karışımlarında, %10 MA ikemeli (10MA kodlu) numuneler; aynı çimento dozajında karışımın %90 oranında S-MA ve %10 oranında mermer atığı (MA) içermesiyle üretilmiştir.

Tablo 2'de belirtilen şartlarda üretilmesi planlanan numuneler için ÇMD bileşenleri laboratuvar tipi bir karıştırıcıdan (hacim= 20,8 lt ve karıştırma hızı= 105 devir/dk) faydalanılarak 7 dk titiz bir biçimde karıştırılmıştır (Şekil 3a). Homojen hale getirilen karışımlar alt bölgesinde drenaj delikleri bulunan silindirik

(5x10 cm) kalıplara 2 aşamada (1: alt yarı seviye ve 2: üst yarı seviye) doldurularak sıkılama işlemine tabi tutulmuş, ardından numunelerin bünyelerindeki fazla suyun uzaklaştırılması amacıyla 1 gün drenaj tablalarında bekletilmiştir (Şekil 3b). Son olarak, kür koşullarının (sıcaklık= 20°C ve nem= %85) sağlanması için 180 güne kadar kür dolabında saklanmıştır (Şekil 3c).

Tablo 2. Çizelge 3. ÇMD numunelerine ait karışım tasarım parametreleri

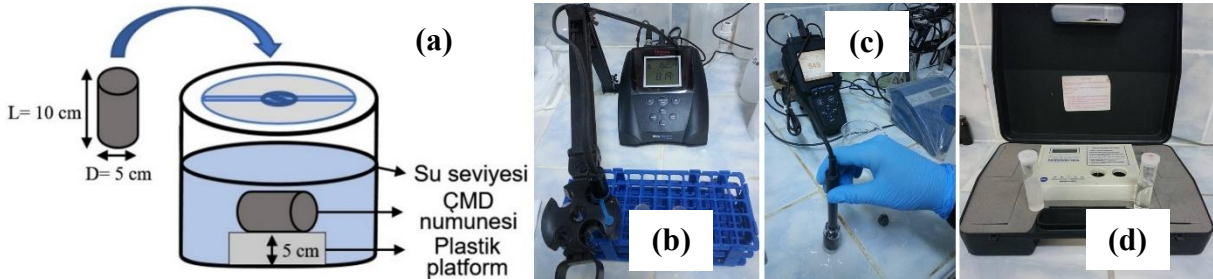
Numune Kodu	İkame oranı (%)	Bağlayıcı oranı (%)	Katı oranı (%)	Su/çimento oranı	Slamp (cm)
Kontrol	0		73,70	4,20	
10MA	10	8,5	74,33	4,06	19,05



Şekil 3. ÇMD karıştırıcısı (a), drenaj (b) ve kür işlemi (c)

2.3. Dinamik tank liçi (DTL) testi

Kür işlemi tamamlanan 2 farklı karışım tipinde (Kontrol ve 10MA) imal edilen ÇMD numuneleri kalıplarından çıkarılmış, numunelerin yüzeylerinde düzeltme işlemi gerçekleştirilerek alt-üst yüzeylerinin paralelliği sağlanmış ve kumpas kullanılarak boyları (h) ölçülmüştür. Yılmaz vd. (2021)'nin çalışmasında tüm detayları bulunan DTL testleri; ASTM ve US-EPA tarafından uygulanması tavsiye edilen standartlar (ASTM C1308-08, 2009; US-EPA 1315, 2013) uyarınca her kap içerisinde 1'er tane (Şekil 4a) ve karışım tipinden bağımsız olarak 3'er tane numune kullanılmak suretiyle 6 farklı liç süresinde (30-60-90-180-270-360 gün) yürütülmüştür. Kapların ağzı kapalı olarak gerçekleştirilen testlerde her liç süresi tamamlandığında su numuneleri alınarak fitre edilmiş (0,45 µm'lik vakum filtre) ve numuneler yeni kaplara yerleştirilerek üzerlerine taze saf su doldurulmuştur. Filtrasyon ile edinilen su numuneleri üzerinde sırasıyla pH (Şekil 4b), elektrik iletkenliği (EC) (Şekil 4c) ve sülfat (SO₄²⁻) (Şekil 4d) analizleri uygulanmıştır.



Şekil 4. Şematik olarak DTL testi (a) (Yılmaz ve Ercikdi, 2022), pH (b), EC (c) ve SO₄²⁻ (c) analizleri

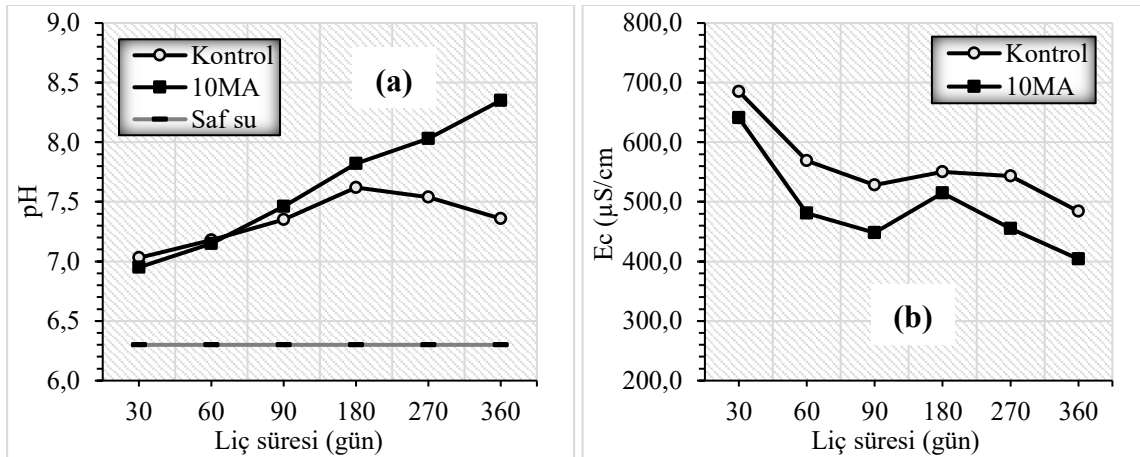
2.4. Porozite (MIP) Testi

ÇMD'nin mikroyapısında (porozite, vb.) meydana gelen değişimlerin DTL testinden yararlanılarak incelenen çevresel parametrelere etkisinin irdelenebilmesi için numunenin bütünlüğüne herhangi bir zarar verilmeyen 180 günlük Kontrol ve 10MA kodlu macun dolgu numuneleri MIP (Micromeritics Autopore IV 9410) cihazı vasıtasıyla porozite testlerine tabi tutulmuştur. ASTM D 4404-18 (2018) standardı çerçevesinde gerçekleştirilen testler öncesinde numunelere; hem hidrasyon süreçlerinin sona erdirilmesi hem de tam olarak kurumaları için etüvde (süre= 60 saat, sıcaklık= 50°C) kurutma işlemi uygulanmıştır.

3. Bulgular ve Tartışma

3.1. pH Bulguları

Şekil 5a, 6 farklı liç süresi (30-60-90-180-270-360 gün) boyunca DTL testi uygulanan Kontrol ve 10MA kodlu ÇMD numunelerinden elde edilen su numunelerinin pH değişimlerini göstermektedir. 30 günlük liç süresi sonunda 6,95 ve 7,03 seviyelerinde pH değerleri ölçülen ÇMD'lerin sonraki liç süreleri (60-360 gün) boyunca alkali seviyelerde seyrettiği gözlemlenmiştir. 30-180 günlük liç süreleri sonunda Kontrol ve 10MA numunelerinin bulunduğu kaplardan alınan ve filtre edilen su örneklerinin alkalilik derecesi yükselme eğilimi göstermesiyle birlikte numunelerin pH seviyelerinin birbirine çok yakın (Kontrol= 7,03-7,62 ve 10MA= 6,95-7,82) olduğu tespit edilmiştir. Oysaki sonraki liç süreleri (270 ve 360 gün) boyunca Kontrol ÇMD numunelerinin pH değerlerinde düşüş trendi gözlemlenirken, S-MA yerine %10 MA ikame edilen ÇMD numunelerinde pH artışı 8,35'e kadar devam etmiştir. 360 gün sonunda ortaya çıkan pH bulguları kıyaslandığında, %10 MA ikameli ÇMD numunelerinden alınan su numunelerinin Kontrol numunesine nazaran %13,5 daha yüksek pH değerine sahip olduğu belirlenmiştir (**Şekil 5a**). Bu faydalı etki, S-MA'ya nazaran MA'nın daha küçük boyutlu ($D_{80}= 51,0 \mu\text{m} < 68,5 \mu\text{m}$) tanelerden oluşması (**Şekil 2**) ve böylece yüzey alanının daha yüksek olması ($4670 \text{ cm}^2/\text{g} > 4440 \text{ cm}^2/\text{g}$) ve kayda değer biçimde daha yüksek nötrleştirme potansiyeli (NNP= $987,8 \text{ kg CaCO}_3/\text{ton atık} > 485,8 \text{ kg CaCO}_3/\text{ton atık}$) (**Tablo 1**) taşınması ile açıklanabilir. Bu bulgularla uyumlu olarak, ÇMD içerisinde kullanılan bileşenin (MA) nötrleştirme kabiliyetinin yüzey alanındaki büyüme ile arttığı bildirilmiştir (**Potgieter-Vermaak vd., 2006**). Dahası, önceki araştırmacıların ortaya koyduğu bulgular ile paralellik gösterdiği üzere (**Jones ve Cetin, 2017**), mermer atığının içerdiği kalsit (CaCO_3) mineralinin çözünmesi 10MA kodlu numunenin DTL testi vasıtasıyla edinilen su örneklerinin baziklik derecesini yükselttiği söylenebilir (**Yılmaz ve Erçikdi, 2022**).



Şekil 5. DTL testi uygulanan ÇMD numunelerinin pH (a) ve EC (b) bulguları

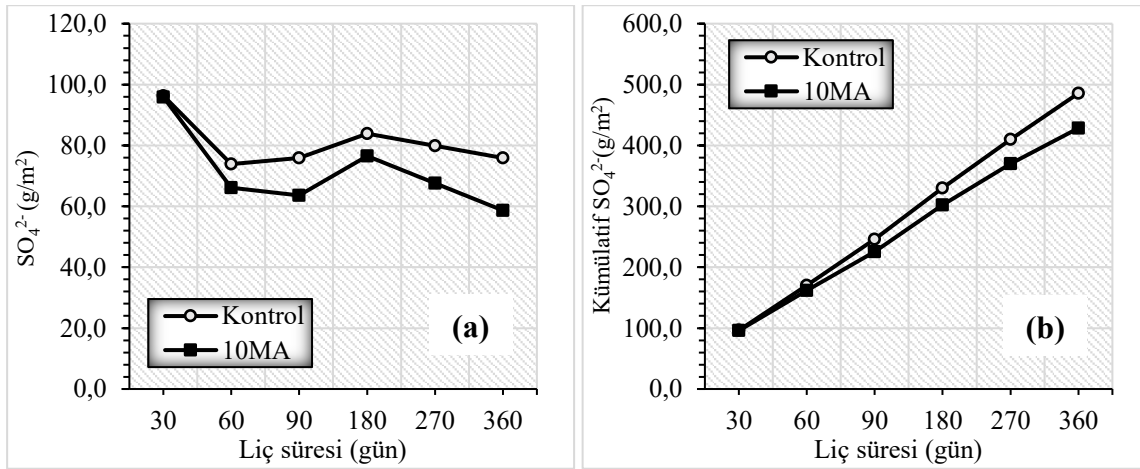
3.2. Elektrik İletkenliği (EC) Bulguları

Kontrol ve 10MA kodlu ÇMD numunelerinin 30-360 günlük liç süreleri boyunca DTL testine tabi tutulması sonucunda elde edilen su örnekleri üzerinde yürütülen elektrik iletkenliği (EC) testi bulguları **Şekil 5b**'de sunulmuştur. ÇMD'lere ait su numunelerinin EC değerlerinin 30-360 gün aralığında genel olarak düşüş eğiliminde olmasıyla birlikte liç süresi ve karışım tipinden bağımsız olarak EC değerlerinin 404-685 $\mu\text{S}/\text{cm}$ arasında değiştiği görülmektedir (**Şekil 5b**). EC değerlerindeki azalma, önceki araştırmacıların bulgularıyla tutarlı olarak (**Hakkou et al. 2009; Taha et al. 2019**), pH değerindeki artışla bağlantılı olarak suda çözünen iyonların (örneğin Ca^{2+} , Mg^{2+} ve SO_4^{2-}) salınımındaki azalmaya bağlanabilir; zira bu iyonların iletkenliğin gelişimini önemli ölçüde etkilemesi beklenmektedir. MA ikamesinin EC değişimi üzerindeki etkisine bakıldığında, tüm liç sürelerinde Kontrol'e kıyasla daha düşük iletkenlik değerleri ölçülmüştür. Şöyle ki; Kontrol numunelerinden elde edilen su numunelerinde 484-685 $\mu\text{S}/\text{cm}$ aralığında EC değerleri ölçülürken, 10MA numunelerinde ölçülen iletkenlik değerlerinin Kontrol ile karşılaştırıldığında %16,20'ye kadar daha düşük olan 404-641 $\mu\text{S}/\text{cm}$ seviyesindedir (**Şekil 5b**). Bunlara ek olarak, dünya sağlık örgütü tarafından yeraltı

suları için tavsiye edilen izin verilebilir iletkenlik değerinin 1400 $\mu\text{S}/\text{cm}$ olduğu göz önünde bulundurulduğunda (WHO, 2011), bu çalışmada kaydedilen EC değerlerinin limit değerinden oldukça altında kaldığı açıkça görülmektedir (Annapoorna ve Janardhana, 2015).

3.3. Sülfat (SO_4^{2-}) Bulguları

Şekil 6'da 30-360 günlük DTL testleri akabinde fitre edilen su numuneleri üzerinde gerçekleştirilen sülfat analizleri sonucunda normal (a) ve kümülatif (b) sülfat (SO_4^{2-}) bulguları verilmiştir. ÇMD'nin baskın bileşeni olan S-MA bünyesinde yer alan piritin okside olması kaynaklı birincil ürün olarak üretilen sülfat (SO_4^{2-}) değerleri incelendiğinde, karışım tipinden bağımsız olarak 30-360 günlük liç süreleri boyunca su örneklerine salınan sülfat içeriklerinin 58,64-96,33 g/m^2 seviyesinde olduğu tespit edilmiştir. Şekil 5a'da verilmiş olan pH değerleri ile genel olarak uyum içerisinde olduğu gözlemlenen SO_4^{2-} bulguları dikkate alındığında, yükselen alkalilik ile SO_4^{2-} salınımının azaldığı gözlemlenmiştir (Şekil 6a). Kontrol numunelerinden suya geçen sülfat iyonu miktarları ile karşılaştırılacak olursa, liç süresinden bağımsız olarak 10MA kodlu numunelerden salınan sülfat miktarının %22,7 oranında daha düşük olduğu ortaya konmuştur. Ayrıca, Şekil 6b'de sergilenmekte olan kümülatif sülfat değerleri incelendiğinde, 90 güne kadar numunelerden suya salınan sülfat miktarlarının birbirine çok yakın seyrettiği, buna karşın, ilerleyen liç süreleri boyunca sülfat miktarları arasındaki farkın giderek açıldığı görülmektedir. Şöyle ki; DTL testleri tamamlandığında kontrolden 485,65 g/m^2 sülfat iyonu salınımı gerçekleşirken, aynı süre sonunda 10MA numunesinden %11,8 oranında daha düşük (428,36 g/m^2) salınım gerçekleşmiştir (Şekil 6b). 10MA numunesinde meydana gelen nispeten daha düşük SO_4^{2-} salınımı, mermer atığı bünyesinde bulunan kalsit mineralinin çözünmesi ile ortaya çıkan Ca^{2+} iyonları ile pirit oksidasyonunun ortaya çıkardığı sülfat iyonlarının jips minerali şeklinde bağlanmasıyla açıklanabilir. Sonraki bölümde detaylı bir şekilde açıklanacağı üzere, %10 MA ikamesinin ÇMD numunesinin toplam ve kademeli porozitelerini azaltması (Şekil 7), numunenin geçirgenliğinin kısıtlanarak oksidatif mekanizmaları yavaşlatmasını ve böylece sülfat (SO_4^{2-}) salınımının Kontrole kıyasla daha düşük seviyede kalmasını desteklemektedir (Şekil 6) (Mangane vd., 2018; Yılmaz vd., 2018).

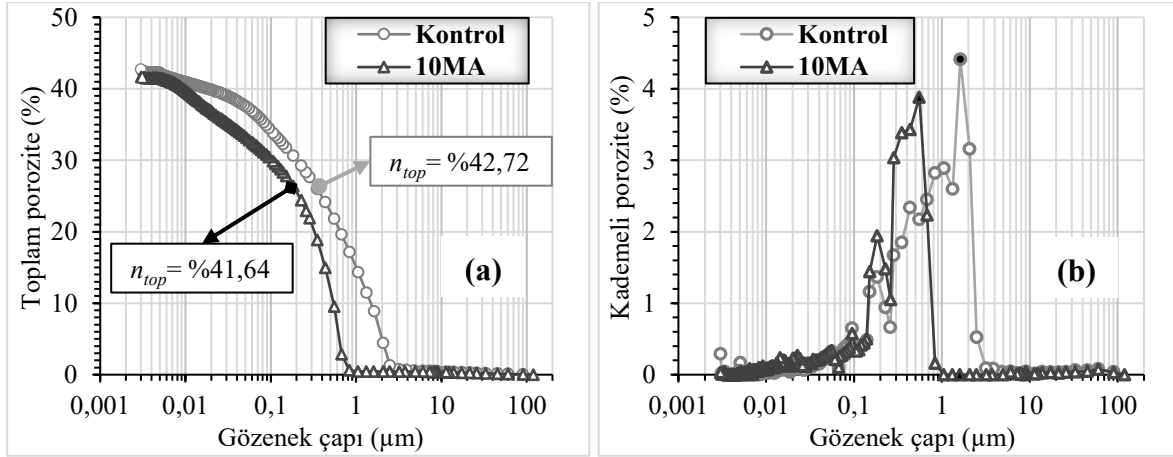


Şekil 6. DTL testi uygulanan ÇMD numunelerinin normal (a) ve kümülatif (b) sülfat (SO_4^{2-}) bulguları

3.3. Porozite (MIP) Bulguları

DTL testi uygulanan ÇMD numunelerinin (Kontrol ve 10MA) 180 gün sonunda gerçekleştirilen MIP testi sonucunda elde edilen toplam (a) ve kademeli (b) porozite bulguları Şekil 7'de sergilenmektedir. Numunelerin toplam porozite (n_{top}) değerlerinin Kontrol ve 10MA için sırasıyla %42,72 ve %41,64 olduğu belirlenmiştir. MA ikamesinin ÇMD'nin mikroyapı performansını nispeten olumlu etkilediği Şekil 7a'dan görülmektedir. Şöyle ki; ÇMD karışımına %10 oranında MA ikame edilmesiyle birlikte n_{top} değerinin %2,5 oranında azaldığı hesaplanmıştır. Toplam porozitedeki bu azalma, S-MA taneleri ile karşılaştırıldığında, MA tanelerinin daha ince yapıda olması (Şekil 2) ve böylelikle MA'nın daha büyük yüzey alanı ($4670 > 4440 \text{ cm}^2/\text{g}$) göstermesi sonucunda boşluk doldurucu karakter sergileyerek daha az gözenek içeren daha kompakt bir ÇMD yapısı oluşturulması ile bağlantılandırılabilir. Bu durum, 10MA numunesinin Kontrole nazaran daha düşük su-

çimento oranına ($4,06 < 4,20$) ve daha yüksek katı oranına ($74,33 > 73,70$) sahip olması ile doğrulanmaktadır (Tablo 2) (Ercikdi vd., 2013; Celik vd., 2014; Yılmaz vd., 2018). Şekil 7b’de sunulmuş olan kademeli porozite bulguları değerlendirildiğinde, 10MA’nın kademeli porozite sonuçlarının toplam porozite sonuçları ile uyum gösterdiği anlaşılmaktadır. En yüksek boyutlu gözeneklerin toplam porozite içindeki payına bakıldığında, Kontrol numunesinin %4,41’ini kapsadığı, buna karşın, MA ikamesiyle bu oranın %3,88’e gerilediği gözlemlenmiştir. Dahası, MA içeren ÇMD numunesinde gözenek çaplarının küçüldüğü Şekil 7b’den açıkça görülmektedir.



Şekil 7. DTL testi uygulanan ÇMD numunelerinin 180 gündeki toplam (a) ve kademeli (b) porozite bulguları

4. Sonuçlar

Bu laboratuvar araştırması, ÇMD’nin uzun dönem çevresel performansının değerlendirilmesi amacıyla %8,5 çimento dozajında imal edilen ve 180 gün boyunca kürlenmiş ÇMD numunelerine (Kontrol ve 10MA) 360 günlük liç süresine kadar dinamik tank liçi (DTL) testi uygulanması sonucunda filtrasyon işlemi aracılığıyla elde edilen su örneklerinin pH, elektrik iletkenlik (EC) ve sülfat (SO_4^{2-}) analizlerinin gerçekleştirilmesini içermektedir. Ayrıca, ilgili kür süresi sonunda numuneler üzerinde MIP cihazı aracılığıyla porozite testleri yürütülmüştür. Sonuçlar irdelendiğinde, tüm numunelerin alkali pH koşullarında seyrettiği, 10MA kodlu numunelerin özellikle ilerleyen liç sürelerinde Kontrol’e nazaran daha yüksek pH değerleri gösterdiği tespit edilmiştir. Karışım türü ve liç süresine bakılmaksızın 404-685 $\mu S/cm$ arasında EC değerlerinin ölçüldüğü ve MA ikamesinin EC değerlerini %16,2’ye kadar azalttığı belirlenmiştir. Benzer şekilde, 10MA kodlu ÇMD numunelerinde Kontrol’e kıyasla su örneklerine geçen sülfat iyonu miktarı %22,7’ye kadar düşmüştür. Porozite bulgularına bakıldığında, Kontrol numunesi 180 gün sonunda %42,72 oranında toplam poroziteye sahipken, 10MA kodlu ÇMD’de bu oran %2,5 azalmayla %41,64 olarak ölçülmüştür. ÇMD’de kullanılan %10 MA ikamesinin toplam poroziteyi destekler nitelikte kademeli porozite değerlerini de azalttığı belirlenmiştir. Tüm bu bulgular ışığında, ÇMD bileşeni olarak %10 mermer atığı ikamesinin ÇMD’nin çevresel kalitesi üzerinde olumlu katkısının olduğu söylenebilir.

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İçme Suyu Arıtımında Alternatif Bir Filtre Ortamı Olarak Borla Sinterlenmiş Pomzanın Kullanılabilirliğinin Araştırılması

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Özet

Bu bildiri, içme suyu arıtımında alternatif filtre medyası geliştirmeye yönelik tez çalışmasının mevcut aşamasını ve ilgili literatürün eleştirel sentezini sunmaktadır. Çalışmada silisli kum referans medyası ile farklı fraksiyonlardaki pomza tanelerinden bor bağlayıcısı kullanılarak sinterlenmiş, stratifiye tuğla formunda bir filtre medyası tasarlanmıştır. Amaç, askıda katı madde tutulması ile birlikte yüzey özellikleri ayarlanabilir, mekanik olarak daha kararlı ve yeniden kullanılabilir bir medya geliştirmektir. Literatür değerlendirmesi, pomzanın kumla karşılaştırıldığında daha yüksek iç porozite, yüzey pürüzlülüğü ve düşük yoğunluk sunduğunu; modifiye pomzanın ise florür, arsenat, doğal organik madde ve mikroplastik gibi kirleticilerin gideriminde ek işlev kazanabildiğini göstermektedir. Buna karşılık gevşek granüler pomza sistemlerinde tane segregasyonu, filtre yatağındaki basınç düşümünün izlenmesi ve rejenerasyon gibi işletme sorunları devam etmektedir. Bu nedenle önerilen borla bağlanmış sinterlenmiş tasarım, katmanlı tane boyu dağılımını sabitleyen ve uzun dönem filtrasyon davranışının ayrıntılı olarak test edilmesine olanak veren özgün bir yaklaşım olarak ele alınmıştır. Bildiride, medya karakterizasyon planı ve performans göstergeleri ortaya konulmuş; ayrıca literatürde borla bağlanmış sinterlenmiş pomza esaslı filtre ortamlarının içme suyu arıtımındaki uygulanabilirliğine ilişkin çalışmaların sınırlı olduğu vurgulanmıştır.

Anahtar Kelimeler; Adsorpsiyon, filtre medyası, içme suyu, pomza, sinterleme

Investigation of the Usability of Boron-Bonded Sintered Pumice as an Alternative Filter Medium in Drinking Water Treatment

Abstract

This paper presents the current stage of an ongoing thesis study aimed at developing an alternative filter medium for drinking water treatment and provides a critical synthesis of the relevant literature. In the proposed approach, a stratified brick-type filter medium is designed by combining pumice particles of different size fractions and sintering them with a boron-based binder, while silica sand is used as the reference medium. The objective is to develop a mechanically stable, reusable and surface-tunable medium capable of retaining suspended solids and potentially enhancing ion removal through controlled surface properties. The reviewed literature indicates that pumice offers higher intraparticle porosity, greater surface roughness and lower density than conventional sand, while modified pumice can additionally target fluoride, arsenate, natural organic matter and microplastics. However, loose granular pumice systems still face operational limitations such as particle segregation, head-loss control and regeneration. Therefore, the proposed boron-bonded sintered design is discussed as an original approach that stabilizes the layered particle-size distribution and enables systematic evaluation of long-term filtration behaviour. In the paper, the media characterization plan and performance indicators were presented; moreover, it was emphasized that studies on the applicability of boron-bonded sintered pumice-based filter media in drinking water treatment are limited in the literature.

Keywords; Adsorption, drinking water, filter media, pumice, sintering

1. Giriş

İçme suyu arıtımında filtrasyon, koagülasyon, çöktürme ve dezenfeksiyon gibi ünitelerle birlikte çok bariyerli arıtma yaklaşımının temel bileşenlerinden biridir. Granüler filtrasyon yalnızca bulanıklık ve askıda katı madde giderimi için değil, aynı zamanda patojen yükünün azaltılması ve izleyen dezenfeksiyon basamağının etkinleştirilmesi açısından da kritik öneme sahiptir. Bu nedenle filtre yatağında kullanılan medyanın tane boyu dağılımı, şekli, yüzey özellikleri, porozitesi ve işletme ömrü doğrudan proses performansını belirlemektedir (Cescon & Jiang, 2020; Wyczarska-Kokota et al., 2024; Arora et al., 2025).

Konvansiyonel hızlı kum filtreleri pratikte yaygın ve güvenilir sistemler olmakla birlikte, kompakt tane yapısı ve düşük iç porozite nedeniyle özellikle yüzey temelli tutunma süreçlerinde sınırlı bir davranış sergileyebilmektedir. Ayrıca filtre yatağının yaşlanması, tane yüzeyi üzerinde organik ve inorganik birikimlerin gelişmesi, yatak içi karışma ve baş kaybının (head loss, pressure drop) artması gibi olgular, medyanın başlangıçta tasarlanan hidrolik ve adsorptif özelliklerinden sapmasına yol açabilmektedir (Wyczarska-Kokota et al., 2024). Bu nedenle son yıllarda, mevcut altyapıya büyük yapısal değişiklik getirmeden daha yüksek verim veya daha düşük baş kaybı sağlayabilecek alternatif medya arayışı hız kazanmıştır (Cescon & Jiang, 2020).

Pomza bu bağlamda dikkat çeken doğal malzemelerden biridir. Volkanik kökenli, hafif ve gözenekli yapısı sayesinde yüksek iç porozite, düzensiz yüzey pürüzlülüğü, düşük yoğunluk ve kolay işlenebilirlik sunar. Türkiye'nin pomza kaynakları açısından güçlü bir potansiyele sahip olması da bu malzemenin yerli, ekonomik ve sürdürülebilir bir alternatif olarak değerlendirilmesini anlamlı kılmaktadır (Aksay Kılınç, Cöcen, & Akar, 2016). Nitekim Farizoğlu, Nuhoglu, Yıldız ve Keskinler (2003), hızlı filtrasyon koşullarında pomza yatağının aynı koşullardaki kuma göre daha yüksek bulanıklık giderimi ve daha düşük baş kaybı sağlayabildiğini göstermiştir. Benzer biçimde Şahin, Anapalı ve Hanay (1998), kum-çakıl filtre sistemlerinde pomza kullanılan düzenlemenin daha düşük sediment çıkışı ve daha uzun kullanım süresi sağlayabildiğini rapor etmiştir.

Pomzanın kullanım alanı yalnızca fiziksel partikül tutmaya dayalı filtrasyonla sınırlı değildir. Literatürde demir oksit, alüminyum esaslı bileşikler, MgO veya lantan bazlı fazlarla modifiye edilen pomzanın doğal organik madde, florür, arsenat ve mikroplastik gibi kirleticilerin gideriminde işlevsel hale getirilebildiği gösterilmiştir (Kitis et al., 2007; Zhang et al., 2021; Deng et al., 2024). Bu bulgular, pomzanın taşıyıcı veya aktif medya olarak yalnızca makro gözenekli bir dolgu malzemesi değil, aynı zamanda yüzey kimyası ayarlanabilir bir fonksiyonel arıtım matrisi olarak da değerlendirilebileceğini ortaya koymaktadır.

Özellikle son yıllarda mikroplastik ve nanoplastik gibi yeni nesil kirleticilerin içme suyu arıtma zincirindeki davranışına ilişkin çalışmalar, medya yüzey pürüzlülüğü, boşluk mimarisi, organik madde kaplanması ve yüzey yükünün ayırma performansında belirleyici olduğunu göstermiştir. Pilot ölçekli içme suyu arıtma tesisi çalışmalarında kum ve aktif karbon filtrasyonunun nanoplastik gideriminde etkili olduğu; tutunmanın yalnızca eleme ile değil, yüzey pürüzlülüğü, gözenek içi hapsolme ve yük etkileşimleriyle de gerçekleştiği bildirilmiştir (Ramirez Arenas et al., 2022; Pulido-Reyes et al., 2022). Buna ek olarak, sürdürülebilir biçimde modifiye edilmiş granüler medyaların doğal organik madde, bulanıklık ve mikroplastik giderimini aynı anda iyileştirebildiği gösterilmiştir (Lapointe et al., 2025).

Buna rağmen mevcut çalışmaların önemli bölümü gevşek granüler pomza, pomza tozu veya kimyasal olarak kaplanmış pomza taneleri üzerine yoğunlaşmaktadır. Katmanlı tane boyu dağılımını koruyan, mekanik bütünlüğü yüksek, yeniden kullanım potansiyeli taşıyan ve filtre yatağında segregasyon riskini azaltan yekpare pomza gövdelerine ilişkin çalışma sayısı sınırlıdır. Bu araştırma boşluğundan hareketle, bu bildiride bor bağlayıcısı ile bütünleştirilmiş ve sinterlenmiş stratifiye pomza esaslı bir filtre ortamı önerilmektedir. Çalışmanın amacı, geliştirilen medyanın tasarım gerekçesini, karakterizasyon yaklaşımını ve performans değerlendirme çerçevesini ortaya koymak; aynı zamanda içme suyu arıtımında kum medyasına alternatif oluşturma potansiyelini literatür temelli olarak tartışmaktır. Bu nedenle bildiri, tamamlanmakta olan tez çalışmasının ön değerlendirme ve sentez niteliğindeki bir tam metin sunumudur.

2. Materyal ve Yöntem

Çalışmada referans filtre medyası olarak bir içme suyu arıtma tesisinde kullanılan standart silisli kum (SK) dikkate alınmış; alternatif medya bileşenleri olarak ise üç farklı tane boyu fraksiyonuna ayrılmış pomza kullanılmıştır. Söz konusu pomza fraksiyonları, farklı boyuttaki partiküllerin farklı derinliklerde tutulmasını hedefleyen katmanlı bir yerleşim anlayışıyla değerlendirilmiştir. Bu yaklaşımda kaba fraksiyonun giriş

bölgesinde, daha ince fraksiyonların ise aşağı katmanlarda yer alması öngörülmüş; böylece hem yüzeysel tıkanmanın geciktirilmesi hem de yatağın derinliklerine yayılan bir tutma davranışı elde edilmesi amaçlanmıştır.



Şekil 1: Borla bağlanmış sinterlenmiş pomza

Bu çalışmanın özgün yönü, gevşek granüler pomza karışımı yerine, seçilen fraksiyonların bor esaslı bir bağlayıcı yardımıyla belirli bir geometri içerisinde bütünleştirilmesi ve sinterlenerek tuğla benzeri yekpare filtre elemanlarına dönüştürülmesidir. Bor bağlayıcısının kullanılmasındaki temel yaklaşım, katmanlı tane düzenini sabitlemek, taşıma ve yerleştirme sırasında fraksiyonların ayrışmasını önlemek ve kontrollü bir gözenek mimarisi ile mekanik dayanımı birlikte sağlayabilmektir. Bu tasarım, granüler pompaya özgü operasyonel kararsızlıkların azaltılmasına yönelik deneysel bir çözüm önerisi sunmaktadır.

Tablo 1. Çalışmada kullanılan medya kodları ve tasarım içindeki işlevleri.

Kod	Tanım	Tane boyutu	Tasarım içindeki rolü
SK	Standart silisli kum	Referans medya	Mevcut tesis medyası ile karşılaştırma
Pi1	İri taneli pomza	-8 mm +3 mm	Giriş bölgesinde kaba partikül tutulması ve hidrolik geçişin korunması
PO2	Orta taneli pomza	-2 mm +1 mm	Ara katmanda derin filtrasyon ve yük dağılımı
PK3	İnce taneli pomza	<1 mm	Alt katmanda ince partikül ve yüzey temelli tutunmanın artırılması

Deneysel değerlendirme çerçevesinde medya karakterizasyonu ve performans testleri iki ana grupta ele alınmaktadır. Birinci grupta, medyanın yapısal özelliklerini belirlemeye yönelik analizler yer almaktadır: tane boyu dağılımı, görünür yoğunluk ve yığın yoğunluğu, su emme davranışı, mineralojik yapı (XRD), yüzey morfolojisi (SEM/EDS), özgül yüzey alanı ve gözenek dağılımı (BET, t-Plot ve BJH), ayrıca gerekiyorsa zeta potansiyel ve basınç dayanımı ölçümleri. İkinci grupta ise proses performansını ortaya koyacak hidrolik ve kalite parametreleri bulunmaktadır: bulanıklık, askıda katı madde, seçilmiş iyonların giderim verimi, baş kaybı gelişimi, tıkanmaya kadar çalışma süresi ve geri yıkama ya da rejenerasyon sonrası performansın korunumu.

Bu bildiri kapsamındaki değerlendirme, tamamlanmakta olan tez çalışmasının mevcut aşamasına karşılık geldiğinden, burada tam ölçekli performans verileri yerine deneysel tasarımın teknik gerekçesi ve literatürle uyumlu hipotezleri sunulmuştur. Dolayısıyla aşağıdaki tartışma bölümü, geliştirilen medyanın beklenen davranışını önceki çalışmaların bulguları ile birlikte yorumlayan bir ön teknik çerçeve sunmaktadır.

3. Bulgular ve Tartışma

3.1. Seçilmiş literatürün çalışmanın tasarımına katkısı

Tablo 2, pomza ve alternatif granüler medya çalışmalarından seçilmiş örnekleri özetlemekte ve önerilen borla bağlanmış sinterlenmiş pomza tasarımı açısından temel çıkarımları göstermektedir.

Tablo 2. Çalışmanın kuramsal çerçevesini besleyen seçilmiş literatür.

Çalışma	Odak	Başlıca bulgu	Bu çalışma için anlamı
Farizoğlu vd. (2003)	Hızlı filtrasyonda gevşek pomza ve kum	Pomza, aynı koşullarda kuma göre daha yüksek bulanıklık giderimi ve daha düşük baş kaybı göstermiştir.	Pomzanın makro-hidrolik açıdan uygulanabilir bir filtre medyası olduğunu destekler.
Zhang vd. (2021)	MgO ile modifiye pomza ve florür giderimi	Yüzey modifikasyonu, pomzanın adsorptif kapasitesini belirgin biçimde artırmış ve kolon uygulamasında kararlı performans sunmuştur.	Pomzanın yalnızca fiziksel değil, yüzeyi düzenlenmiş fonksiyonel medya olarak da kullanılabileceğini gösterir.
Ramirez Arenas vd. (2022)	Kum ve GAC filtrasyonunda nanoplastikler	Yüzey pürüzlülüğü, gözenek içi hapsolme ve yük etkileşimleri filtrasyon davranışını belirlemiştir.	Medya morfolojisi ve yüzey yükünün yeni nesil kirleticiler için kritik olduğunu gösterir.
Lapointe vd. (2025)	Modifiye granüler medya ile çoklu giderim	Yüzeyi düzenlenmiş granüler medya, eşzamanlı doğal organik madde, bulanıklık ve mikroplastik giderimini iyileştirmiştir.	Borla bağlanmış tasarımın ileride yüzey modifikasyonu ile daha işlevsel hale getirilebileceğine işaret eder.

3.2. Kum ve pomza arasındaki yapısal farkların proses davranışına etkisi

Kum medyasında filtrasyon davranışı ağırlıklı olarak taneler arası boşluklarda gerçekleşen mekanik eleme, derin filtrasyon ve flok yakalanması ile açıklanırken, pomzada bu tabloya tane içi porozite ve yüzey pürüzlülüğü de eklenmektedir. Bu fark, özellikle partiküllerin yalnızca boşluk boyutu ile değil, pürüzlü yüzeyler ve düzensiz boşluklar tarafından da tutulabildiği bir davranış penceresi yaratır. Bu nedenle pomzanın performansı, aynı tane boyu dağılımında dahi kumdan farklı olabilir. Farizoğlu vd. (2003) ve Aksay Kılınç vd. (2016) bu farklılığın baş kaybı gelişimi ve partikül tutma verimi üzerinde belirgin sonuçlar doğurabildiğini göstermektedir.

Bununla birlikte yüksek porozite her zaman otomatik olarak daha iyi performans anlamına gelmez. Gözenek mimarisinin bağlantılılığı, sinterleme sonrası açık porların korunması, bağlayıcı miktarının boşluk hacmini ne ölçüde daralttığı ve su akımının gerçek geçiş yolları gibi değişkenler, filtrasyon verimini belirleyen kritik parametrelerdir. Bu nedenle BET, t-Plot ve BJH verileri medyanın yüzey temelli etkileşim potansiyelini göstermek için yararlı olsa da, baş kaybı ve hidrolik kapasite ile birlikte yorumlanmalıdır. Yalnızca yüksek yüzey alanı elde etmek yeterli değildir; aynı zamanda geçirgenlik korunmalı ve tıkanma hızı makul seviyede tutulmalıdır.

3.3. Stratifiye ve yekpare tasarımın beklenen avantajları

Literatürde gevşek granüler pomza yataklarıyla ilgili olumlu sonuçlar bulunmakla birlikte, pratik uygulamada fraksiyonların zamanla karışması, yerleşim sırasında segregasyon ve geri yıkama sırasında medyanın homojenliğinin bozulması önemli sorunlardır. Bu çalışmada önerilen borla bağlanmış sinterlenmiş tasarımın temel yeniliği, iri, orta ve ince fraksiyonların önceden tanımlanmış katmanlı düzenini sabitlemesidir. Böylece giriş bölgesinde kaba partikül yükü karşılanırken, daha alt katmanlarda ince partikül ve yüzey etkileşimleri için daha elverişli bir ortam korunabilir.

Yekpare geometri aynı zamanda mekanik taşıma, modüler değişim ve rejenerasyon açısından da avantaj sağlayabilir. Gevşek granüler yataklarda görülen medya kaybı, sınıflanma ve yeniden doldurma problemleri, tuğla formunda üretilmiş elemanlarda daha kontrollü hale gelebilir. Bu durum, özellikle post-mining kaynaklı sular ya da değişken karakterli yüzey sularında saha ölçekli uygulama açısından önemlidir. Ancak bu potansiyelin doğrulanabilmesi için basınç dayanımı, kimyasal kararlılık, çözünme davranışı ve çoklu ıslanma-kuruma döngülerine karşı dayanımın deneysel olarak gösterilmesi gerekir.

3.4. Yüzey kimyası ve yeni nesil kirleticiler açısından değerlendirme

Pomza esaslı medyaların içme suyu arıtımındaki geleceği yalnızca bulanıklık giderimi ile sınırlı değildir. Demir oksit kaplı pomza ile doğal organik madde giderimi (Kitis et al., 2007), arsenik giderimine yönelik metal kaplı pomza çalışmaları (Nasseri & Heidari, 2012) ve MgO ya da lantan esaslı modifiye pomza örnekleri (Zhang et al., 2021; Deng et al., 2024), yüzey fonksiyonelliğinin doğru tasarlanması halinde bu medyanın seçici adsorpsiyon davranışı gösterebildiğini ortaya koymaktadır. Bu durum, önerilen borla bağlanmış sinterlenmiş gövdenin ilerleyen aşamalarda aktif fazlarla kaplanmasına veya yüzey yükünün ayarlanmasına imkan verebileceğini düşündürmektedir.

Yeni nesil kirleticilere ilişkin çalışmalar ayrıca medya morfolojisinin önemini artırmaktadır. Kum ve aktif karbon filtrasyonunda nanoplastiklerin giderimi; straining, yüzey tutunması, boşluk içinde hapsolme ve elektrostatik etkileşimlerin birlikte rol oynadığı karmaşık bir süreç olarak tanımlanmıştır (Ramirez Arenas et al., 2022; Pulido-Reyes et al., 2022). Bu nedenle geliştirilecek pomza medyasının yalnızca klasik bulanıklık parametreleri ile değil, yüzey yükü kontrollü model kirleticiler ve uzun dönem fouling davranışı ile birlikte değerlendirilmesi, çalışmanın bilimsel katkısını belirgin biçimde artıracaktır.

3.5. Kritik araştırma soruları ve sınırlılıklar

Mevcut aşamada yanıtlanması gereken temel araştırma soruları şunlardır: (i) bor bağlayıcısı ve sinterleme koşulları açık por yapısını hangi ölçüde korumaktadır, (ii) yekpare medyanın geçirgenlik-baş kaybı dengesi gevşek pomza ve silisli kumla karşılaştırıldığında nasıldır, (iii) mekanik dayanım ile arıtma verimi arasında optimum denge hangi bağlayıcı oranı ve tane dizilimi ile sağlanmaktadır, (iv) medya tekrar kullanım ve geri yıkama sonrasında performansını ne ölçüde korumaktadır ve (v) yüzey özellikleri seçilmiş iyonların veya yeni nesil kirleticilerin gideriminde ilave katkı sağlayabilmekte midir.

Bu sorular aynı zamanda çalışmanın mevcut sınırlılıklarını da tanımlamaktadır. Eldeki metin, tez kapsamında geliştirilen medyanın tasarım gerekçesini ve araştırma planını yayınlanabilir, akademik bir çerçevede sunmayı amaçlamaktadır; dolayısıyla burada nihai deneysel performansın tüm sayısal sonuçları raporlanmamıştır. Bununla birlikte literatür sentezi ve özellikle düşük maliyetli, yerli ve fonksiyonel filtre medyası arayışında dikkate değer bir araştırma yönü sunmaktadır.

4. Sonuçlar

Bu çalışma, içme suyu arıtımında alternatif filtre medyası olarak pomzanın yalnızca gevşek granüler formda değil, bor bağlayıcısı ile bütünleştirilmiş ve sinterlenmiş stratifiye bir gövde halinde de değerlendirilebileceğini ortaya koyan bir ön teknik çerçeve sunmaktadır. Literatür; pomzanın kumdan farklı olarak yüksek iç porozite, pürüzlü yüzey ve düşük yoğunluk gibi özellikler sayesinde filtrasyon davranışını iyileştirebileceğini, uygun yüzey modifikasyonları ile de seçici adsorpsiyon yeteneği kazanabileceğini göstermektedir.

Önerilen tasarımın temel katkısı, farklı tane boyu fraksiyonlarını sabit bir katmanlı yapıda birleştirerek derin filtrasyon, hidrolik kararlılık ve mekanik bütünlüğü birlikte hedeflemesidir. Bu yaklaşım, gevşek granüler pomza yataklarında görülen segregasyon ve işletme değişkenliğini azaltma potansiyeline sahiptir.

Bundan sonraki aşamada, medyanın mineralojik ve morfolojik karakterizasyonunun sayısal olarak tamamlanması; geçirgenlik, baş kaybı, bulanıklık giderimi gibi çalışmalar yapılacaktır. Bu veriler, önerilen medyanın saha ölçeğine taşınabilirliğini belirleyecek ana tabanı oluşturacaktır.

Sonuç olarak borla bağlanmış sinterlenmiş pomza yaklaşımı, hem yerli malzeme kullanımını öne çıkarması hem de içme suyu arıtımında çok işlevli medya tasarımına imkan vermesi bakımından dikkat çekici bir araştırma alanı oluşturmaktadır. Özellikle post-mining sahalarından etkilenen su kaynaklarında veya değişken özellikli yüzey sularında, modüler ve yeniden kullanılabilir filtre elemanı geliştirme yönünden önemli bir potansiyel taşımaktadır.

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Madencilik Faaliyetlerinde Rehabilitasyon ve Atık Yönetiminin Hukuki Niteliği

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Özet

Madencilik faaliyetleri, yoğun bir şekilde çevre ile etkileşim içerisinde olduğundan bu etkileşimin hukuk sistemi ile kapsamlı bir şekilde yönetilmesi gerekmektedir. Bu bağlamda rehabilitasyon ve atık yönetimi madencilik faaliyetlerinin her aşamasında etkisini göstermekte ve hukuki yükümlülükler getirmektedir. Bu çalışmada, madencilik faaliyetlerinde atık yönetimi ve rehabilitasyon süreçlerinin hukuki niteliği, çevre hukuku, idare hukuku, maden hukuku çerçevesinde incelenecektir.

Çalışmada, atık yönetimi ve rehabilitasyon kavramlarının hukuki kapsamı incelenecek olup; ruhsatın verilmesi, sürdürülmesi, devri ve sona erdirilmesi süreçlerinde bu yükümlülükler değerlendirilecektir. Rehabilitasyon bedelleri ve teminat uygulamalarının hukuki niteliği ve bu uygulamaların kamu zararlarına karşı mali güvence mi yoksa bir yaptırım mı olduğu tartışılacaktır. Rehabilitasyon ve atık yönetimi yükümlülükleri ruhsatın ayrılmaz bir unsurudur. Dolayısıyla bu yükümlülükler kusura dayalı olmaktan ziyade kusursuz sorumluluk anlayışıyla şekillenmektedir.

Rehabilitasyon ve atık yönetiminde idarenin denetim ve yaptırım yetkilerinin hukuki sınırları; ölçülülük, hukuki güvenlik ve belirlilik ilkeleri çerçevesinde idarenin takdir yetkisi değerlendirilmekte birlikte uygulamada ortaya çıkan belirsizlikler ve hak iddiaları incelenmektedir. Sonuç olarak çalışmanın temel hedefi; madencilik faaliyetlerinde rehabilitasyon ve atık yönetiminin çevresel koruma ile ruhsat güvencesi arasındaki dengeyi belirleyen temel hukuki unsurlardan biri olduğunu ortaya koymaktır.

Anahtar Kelimeler: atık yönetimi, madencilik faaliyetleri, maden hukuku, rehabilitasyon

Legal Nature of Rehabilitation and Waste Management in Mining Activities

Abstract

Mining activities, due to their intensive interaction with the environment, necessitate comprehensive regulation within the legal system. In this context, rehabilitation and waste management manifest their effects at every stage of mining operations and impose legal obligations. This study examines the legal nature of waste management and rehabilitation processes in mining activities within the frameworks of environmental law, administrative law, and mining law.

The study investigates the legal scope of the concepts of waste management and rehabilitation, evaluating these obligations in the processes of granting, maintaining, transferring, and terminating mining licenses. The legal character of rehabilitation fees and financial assurance mechanisms will be discussed, particularly whether these practices constitute financial guarantees against public harm or sanctions. Rehabilitation and waste management obligations are inseparable elements of the mining license. Consequently, these obligations are shaped by the principle of strict liability rather than fault-based responsibility.

The legal boundaries of the administration's supervisory and sanctioning powers in rehabilitation and waste management are assessed within the principles of proportionality, legal certainty, and predictability, alongside the administration's discretionary authority, while also examining uncertainties arising in practice and related claims. Ultimately, the primary objective of this study is to demonstrate that rehabilitation and

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waste management in mining activities represent one of the fundamental legal elements determining the balance between environmental protection and license security.

Keywords: waste management, mining activities, mining law, rehabilitation

1. Giriş

Madencilik faaliyetleri doğası gereği çevre ile yoğun etkileşim içerisindedir. Bu etkileşim, madencilik faaliyetlerinin tüm aşamalarını kapsamaktadır. Bu nedenle, madencilerin çevre ile uyumlu çalışabilmesi ve faaliyetler sonucu bozulan alanların eski haline getirilebilmesi amacıyla rehabilitasyon ve atık yönetimi ile ilgili mevzuatımızda yasal düzenlemeler yer almakta ve güncel ihtiyaçlara bu düzenlemeler sıklıkla değişikliğe uğramaktadır.

Rehabilitasyon ve atık yönetimi, 3213 sayılı Maden Kanunu, 2875 sayılı Çevre Kanunu, Maden Atıkları Yönetmeliği, Çevresel Etki Değerlendirmesi Yönetmeliği, Maden Sahalarında Rehabilitasyon Yönetmeliği gibi kanun ve yönetmeliklerle detaylı olarak düzenlenmiştir. Çevre hukuku, idare hukuku, maden hukuku gibi birçok hukuk disiplini ilgilendiren rehabilitasyon ve atık yönetimi, madencilik faaliyetlerinin sürekliliği ve bu faaliyetlerin çevreyle uyumlu şekilde gerçekleştirilebilmesi için oldukça önemlidir.

Bu çalışmada; rehabilitasyon süreci, rehabilitasyon bedellerinin ödenmesi, rehabilitasyon bedellerinin maden ruhsatlarının devamlılığına etkisi, atık yönetimi, idarenin denetim ve yaptırım yetkisi gibi hususlar ilgili mevzuat düzenlemesi çerçevesinde tartışılmaktadır.

2. Madencilik Faaliyetlerinin Çevre ile İlişkisi

Rehabilitasyon ve atık yönetimi, maden ruhsatının verilmesinden sahadaki faaliyetler sona erene kadar tüm sürecin ayrılmaz bir parçasıdır. Madenin aranması, bulunduğu yerden çıkarılması gibi faaliyetler neticesinde çevrede meydana gelen değişimler ve bozulmalar rehabilitasyon ve atık yönetimi süreçleriyle kontrol altında tutulmaya çalışılmaktadır. Faaliyet alanlarının eski hale getirilmesi/rehabilitasyon edilmesi için mevzuata uygun, çevre bilinciyle çalışılması üretim faaliyetleri kadar hayati öneme sahiptir. Çünkü madenciliğin esas amacı; toplumun refahını artırmak, ülkenin kalkınmasına katkı sağlamak, öz kaynak kullanımıyla dışa bağımlılığı azaltmak olmakla birlikte; sürdürülebilir madencilik politikalarıyla gelecek nesillere yaşanabilir bir ülke bırakabilmektir.

Madencilik faaliyetlerinin çevreye olan etkileri ile ilgili birçok yasal düzenleme mevcuttur. Madencilik ve çevre etkileşimini en aza indirmek amacıyla Çevre Kanunu, Çevresel Etki Değerlendirmesi Yönetmeliği, Maden Kanunu, Maden Yönetmeliği'nde hükümler mevcuttur.

2873 sayılı Çevre Kanunu'nun üçüncü maddesinde; çevrenin korunması, iyileştirilmesi, kirliliğin önlenmesine ilişkin ilkeler düzenlenmiştir. Aynı kanun maddesinin "g" bendinde; *"Kirlenme ve bozulmanın önlenmesi, sınırlandırılması, giderilmesi ve çevrenin iyileştirilmesi için yapılan harcamalar kirlenme veya bozulmaya neden olan tarafından karşılanır. Kirlenmenin kirlenmeyi veya bozulmayı durdurmak, gidermek veya azaltmak için gerekli önlemleri almaması veya bu önlemlerin yetkili makamlarca doğrudan alınması nedeniyle kamu kurum ve kuruluşlarınca yapılan gerekli harcamalar 6183 sayılı Amme Alacaklarının Tahsil Usulü Hakkında Kanun hükümlerine göre kirlenetenden tahsil edilir."* hükmü bulunmaktadır. Bu hüküm, çevreyi kirletenler için sorumluluk öngörmüştür. Çevreyi kirletenler için Çevre Kanunu madde 28/1'de *"Çevreyi kirletenler ve çevreye zarar verenler sebep oldukları kirlenme ve bozulmadan doğan zararlardan dolayı kusur şartı aranmaksızın sorumludurlar."* hükmü yer almaktadır. Çevreyi kirletenler ortaya çıkan zararları tazmin etmekle yükümlüdür. Kirleten öder ilkesi gereği bilinçli ya da bilinçsiz çevreye zarar veren bu zararın giderilmesinde sorumludur.

Yukarıda bahsedilen kirlenme öder ilkesi rehabilitasyon bedelinin hukuki temelini oluşturur. Madenciler, faaliyetlerini sürdürebilmeleri için rehabilitasyon bedelini ödemekle yükümlüdür. Bu bedelin ödenmemesi durumunda Maden Kanunu madde 13 gereğince ruhsat iptal edilir. (Maden Kanunu m.13: *"...Ruhsat ve rehabilitasyon bedelinin tamamının ocak ayının sonuna kadar yatırılmaması halinde yatırılmayan kısmın o yıl haziran ayının son gününe kadar 6183 sayılı Kanunun 51 inci maddesine göre hesaplanacak gecikme zammı oranında artırılarak yatırılması zorunludur, aksi halde ruhsat iptal edilir."*)

3. Rehabilitasyon Kavramının Hukuki Çerçevesi

24.07.2025 tarihli Resmî Gazete’de 7554 kanun numaralı “Bazı Kanunlarda Değişiklik Yapılmasına Dair Kanun” yayımlandı. Yayımlanan kanunda Maden Kanunu’nda değişiklikler yapılmıştır. “Rehabilitasyon”, “rehabilitasyon bedeli hesabı” gibi kavramların tanımları bu değişikliklerle birlikte Maden Kanunu’na eklenmiştir. Rehabilitasyon, 3213 sayılı Maden Kanunu’nun üçüncü maddesinde; “*Madencilik faaliyetleri nedeniyle bozulan, topoğrafyası değişen alanlara yönelik; emniyetli hâle getirme, düzenleme, duraylılığı sağlama, düzeltme, üst toprağı serme, tohum ekme, fidan dikme, arazi yapısı uygun yerlerde rekreasyon alanları oluşturma, bitkilendirme, ağaçlandırma, kimyasal ve fiziksel iyileştirme kapsamında yapılan çalışmalar.*” şeklinde tanımlanmıştır. Madencilik faaliyetlerinde bozulan alanlarda, eski hale getirme ve iyileştirme adına yapılan tüm faaliyetleri rehabilitasyon faaliyeti olarak değerlendirilebilir.

Rehabilitasyon çalışmalarının giderlerinde kullanılmak üzere maden ruhsat sahiplerinden rehabilitasyon bedeli alınmaktadır. Rehabilitasyon bedeli, işletme ruhsat bedeli kadardır ve her yıl ocak ayının sonuna kadar yatırılması zorunludur. Rehabilitasyon bedelinin ocak ayının sonuna kadar yatırılmaması durumunda haziran ayının son gününe kadar gecikme zammı oranında artırılarak yatırılması gerekir. Aksi durumda ruhsat iptal edilir.

Rehabilitasyon bedelleri nemalandırılır ve bu paralar sadece rehabilitasyon için kullanılacaktır. Bu bedeller bankada nemalandırılacak olup minimum faiz oranı Türkiye Cumhuriyeti Merkez Bankası’nın bir aya kadar vadeli olarak açılan mevduatlara uygulanan ağırlıklı ortalama faiz oranının %75’inden düşük olamaz. Rehabilitasyon bedeli ve nema geliri haczedilemez, rehnedilemez ve temlik edilemez. Rehabilitasyon yükümlülüğü kalmayan ruhsat sahiplerine ödedikleri rehabilitasyon bedelinin kullanılmayan kısmı iade edilir. Fakat bu bedel iadesi 6183 sayılı Kanunun 22/A maddesi kapsamında vadesi geçmiş borcun bulunmaması şartına bağlanmıştır.

23.01.20256 tarih 33146 sayılı Resmî Gazete’de *Maden Sahalarında Rehabilitasyon Yönetmeliği* yayımlanmıştır. Yönetmelik, Maden Kanunu çerçevesinde rehabilitasyon bedellerinin tahsili, nemalandırılması, iadesi ile rehabilitasyon uygulamalarına ilişkin usul ve esasları belirlemektedir. Madencilik faaliyetleri sırasında topoğrafyası bozulan veya değişen alanlarda gerçekleştirilecek rehabilitasyon çalışmalarının yürütülmesine, rehabilitasyon bedellerinin tahakkuku, tahsili, nemalandırılması, ödenmesi ve iadesine, rehabilitasyon projesi uygulamalarına yönelik koordinasyon, yetki ve yükümlülüklerle ilişkin usul ve esaslar Maden Sahalarında Rehabilitasyon Yönetmeliği’ne göre yürütülecektir.

Maden Sahalarında Rehabilitasyon Yönetmeliği 11 maddeden oluşmaktadır. Rehabilitasyona ilişkin genel esaslar ve mali hükümler madde 5-7 arasında düzenlenmiştir. Rehabilitasyon projesinin Genel Müdürlüğün onayına sunulması zorunlu kılınmıştır. Hükümden düşen sahalar ve rehabilitasyon yükümlülüğü yerine getirilmeyen sahalarda; rehabilitasyon yükümlülüğü, orman vafındaki alanlarda ilgili orman idaresi, diğer alanlarda ise idare tarafından yerine getirilecektir.

Maden Sahalarında Rehabilitasyon Yönetmeliği’nin dördüncü maddesinde rehabilitasyon projesi; “*Madencilik faaliyetleri sonucunda bozulan alanların; çevresel, ekolojik ve sosyal açıdan güvenli, sürdürülebilir ve çevreyle uyumlu bir yapıya dönüştürülmesini sağlamak amacıyla hazırlanan, bilimsel verilere, mühendislik esaslarına ve sürdürülebilirlik ilkelerine dayanan teknik uygulama yöntemlerini, uygulama takvimini, yatırım bütçesini ve mali kaynak planlamasını içeren, izlenebilir ve ölçülebilir hedefler barındıran bütüncül proje*” şeklinde tanımlanmıştır. Rehabilitasyon projesi Maden ve Petrol İşleri Genel Müdürlüğü onayına sunulur. Özel çevre koruma bölgesi ilan edilen alanlar için ise Çevre, Şehircilik ve İklim Değişikliği Bakanlığının da onayına sunulur. Rehabilitasyon projeleri onaylanmadan sahada rehabilitasyon çalışması yapılamaz. Devlet ormanlarında rehabilitasyon projeleri ise Orman Kanununun 16 ncı Maddesinin Uygulanması Hakkında Yönetmelik kapsamında hazırlanması gerekmektedir.

4. Atık Yönetiminin Hukuki Çerçevesi

Madenlerin aranması, üretime yönelik hazırlık çalışmaları, üretilmesi, sevkiyatı, cevher hazırlama ve zenginleştirme, atıkların bertarafı, ruhsat sahasındaki stoklama/depolama işlemleri, maden işletmelerinin kapatılması ve çevre ile uyumlu hale getirilmesi ile ilgili tüm faaliyetler ve bu faaliyetlere yönelik geçici tesislerin yapılması madencilik faaliyetleri olarak değerlendirilir. Madenlerin aranması, çıkarılması, hazırlanması/zenginleştirilmesi veya depolanması sonucunda ortaya çıkan atıkların çevreye zarar vermeden taşınması, bertaraf edilmesi ve yönetimi için gerekli olan işlemler Maden Atıkları Yönetmeliği hükümlerine göre yapılır.

Maden Atıkları Yönetmeliği'nin dördüncü maddesinde atık, “Üreticisi veya fiilen elinde bulunduran gerçek veya tüzel kişi tarafından çevreye atılan veya bırakılan ya da atılması zorunlu olan herhangi bir madde veya materyal” şeklinde tanımlanmıştır. Madencilik faaliyetlerinden kaynaklanan atıkların çevre ve insan sağlığına zarar vermeyecek şekilde depolanması ve bertaraf edilmesi esastır.

Maden atıklarının toprağa, suya ve çevreye kontrolsüz bırakılması yasaktır. Atıklar doğrudan kanalizasyona verilemez veya diğer atıklarla karıştırılamaz ve atıklar yalnızca lisanslı tesislere gönderilebilir. Maden atık yönetim planı, Bakanlıkça ÇED yeterlik belgesine ya da çevre danışmanlık yeterlik belgesine haiz kurum ve kuruluşlar veya işletmeciler tarafından bu Yönetmeliğin Ek-1'i doğrultusunda hazırlanarak, ÇED sürecinde ÇED raporu ve proje tanıtım dosyası içinde Bakanlığa veya İl Müdürlüklerine işletmeciler tarafından sunulur.

4. Rehabilitasyon ve Atık Yönetiminde İdarenin Denetim ve Yaptırım Yetkileri

İdare tarafından alınan bir bedelin kamu alacağı sayılabilmesi için devlete doğrudan gelir kaydedilebilmesi, 6183 sayılı Kanun kapsamında tahsil edilebilir olması, vergi, resim, harç benzeri mali yükümlülük niteliği taşıması gerekir. Alınan bedelin idari yaptırım olabilmesi için ise hukuka aykırılık sonucu uygulanmalı ve cezalandırma amacı taşınmalıdır. Oysa rehabilitasyon bedeli; devlete gelir amacı taşımaz, kamu zararına karşı güvence sağlar, faaliyet başında ve devamında alınır, iade edilebilir. Tüm bu açıklanan sebeplerle; rehabilitasyon bedeli idari yaptırım değil, mali teminat özelliği taşır ve rehabilitasyon bedeli kamu gücüyle zorunlu kılınmıştır.

Rehabilitasyon yükümlülüğü; kusura dayanmaz, tehlike esastır ve objektif sorumluluk anlayışı taşır. Kusursuz sorumluluk; kişilerin veya kurumların kusuru bulunmadığı halde doğan zarardan sorumlu tutulmasıdır. 2872 sayılı Çevre Kanunu'nun 28. maddesinde “Çevreyi kirletenler ve çevreye zarar verenler, sebep oldukları kirlenme ve bozulmadan doğan zararlardan dolayı kusur şartı aranmaksızın sorumludurlar.” hükmü yer almakta ve kusursuz sorumluluk kavramı somutlaşmaktadır. Dolayısıyla, bir işletme tüm önlemleri almasına rağmen çevresine verdiği zarardan sorumludur fakat sorumluluktan söz edebilmek için zarar ile faaliyet arasında illiyet bağı bulunmalıdır. Kusursuz sorumluluk mutlak değildir; mücbir sebep, zarar görenin ağır kusuru, üçüncü kişinin ağır kusuru gibi durumlarda işletmeciler sorumluluktan kurtulabilir.

Çevre Kanunu'nun 12 nci maddesinde yer alan “Bu Kanun hükümlerine uyulup uyulmadığını denetleme yetkisi Bakanlığa aittir.” hüküm ile denetim yetkisi Çevre ve Şehircilik Bakanlığı'na verilmiştir. Gerektiğinde bu yetki ilgili kurumlara devredilebilmektedir.

Madencilik faaliyetleri sürekli olarak idare tarafından denetlenir. Projeye aykırılık, bedellerin ödenmemesi veya çevre ile ilgili olumsuz durumlarda idare tarafından yaptırım uygulanır. İdarenin yetkisi sınırsız olmamakla birlikte; ölçülük, belirlilik, hukuki güvenlik gibi temel ilkelerle çevrelenmiştir. Bu ilkeler aynı zamanda ruhsat güvencesini de sağlamaktadır.

3213 sayılı Maden Kanunu'nun 11 nci maddesinin birinci fıkrası; “Genel Müdürlük, maden hakları ile ilgili bütün faaliyetlerin yürütülmesini ve vecibelerin yerine getirilmesini kontrol ve denetimini yapmak ve yönlendirmek için teknik ve mali konuları yerinde incelemek maksadıyla ihtisaslaşmış diğer Devlet kuruluşlarından ve üniversitelerden de yararlanarak inceleme raporu hazırlar...” şeklindedir. Madencilik faaliyetleri Maden ve Petrol İşleri Genel Müdürlüğü tarafından sürekli olarak denetlenir.

Maden ve Petrol İşleri Genel Müdürlüğü, rehabilitasyon süreçlerini denetlerken geniş bir takdir yetkisine sahiptir. Ancak bu yetki sınırsız değildir, Anayasa'da güvence altına alınan hukuk devleti ilkesi gereğince idare keyfi işlem yapamaz, yaptırım orantılı olmalıdır ve ruhsat sahibinin kazanılmış hakları korunmalıdır.

4. Sonuçlar

Rehabilitasyon ve atık yönetimi süreçleri; madencilik faaliyetlerinin sürdürülebilir olmasına ve çevreyi korumaya katkı sağlayan, ruhsat güvencesinin tamamlayıcı bir unsurudur.

Rehabilitasyon bedeli, idari yaptırım veya kamu alacağı değil; risk esaslı ve ruhsata bağlı mali güvence mekanizmasıdır. Maden işletme hakkının devamı için rehabilitasyon bedellerinin zamanında ödenmesi ve rehabilitasyon süreçlerinin mevzuata uygun sürdürülmesi gerekmektedir.

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Training and Capacity Building for Post-mining Management

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Abstract

Mining activities leave long-lasting impacts and managing these impacts responsibly and sustainably remains a major challenge for many mining regions worldwide. Mine closure therefore requires the development of new skills, research, and innovative projects to cover this irresponsible need. Future engineers and researchers must be able to design appropriate measures and manage complex challenges, risk assessment, design mitigation and remediation solutions, associated with mine closure and post-mining procedures. Within this framework, the COST project REMINDNET aims to promote and strengthen knowledge related to post-mining management. With many mines closure expected in the coming years it is urgent to construct European education program for bachelor's students, post-graduate engineers and master's students to face the demands in the domain post-mining risk management, remediation and reclamation of post-mining lands. Different actions are carried out by the REMINDNET such as best practices documents, creating a European post-mining network, etc. The paper presents the different actions for improving the training capacity and the perspectives. The results shown that the knowledge gained in these courses and allowing better understanding the topics of post-mining.

Keywords: Post-mining, Education, New skills, Research

1. Introduction

Mining activities leave long-lasting impacts and managing these impacts responsibly and sustainably remains a major challenge for many mining regions worldwide. This is particularly true in several European countries (Figure 1), where mining activities have declined and mines have closed for economic and social reasons. Furthermore, the European Union's goal of achieving climate neutrality by 2050 has accelerated coal phase-out efforts in regions historically shaped by mining and heavy industry across Europe (Figure 2).

Mine closure therefore requires the development of new skills, research, and innovative projects to cover this irresponsible need. Future engineers and researchers must be able to design appropriate measures and manage complex challenges, risk assessment, design mitigation and remediation solutions, associated with mine closure and post-mining procedures. The training approach and the education must integrate scientific and engineering expertise at the intersection of mine surveying, land surveying, and geo-engineering.

2. REMINDNET Project

REMINDNET (**R**ecovery of **M**ining **D**istrict **N**etwork) is a COST Action, a research network funded by the European Cooperation in Science and Technology. It comprises over 130 scientists and engineers from more than 60 organizations across 37 countries, mainly in the EU. The network focuses on the legislation, governance and management of mine legacies, as well as financing, rehabilitation and monitoring techniques, with the aim of improving implementation to minimize post-closure mining legacies (REMINDNET, 2024).

The ambition of the network is to Map of Europe showing closed and operating mines. The green circles represent the calculated amount of waste rock where the largest circles represent more than 500 Mt of waste rock. Diamonds represents smaller mines and the colours represents type of ore; blue for iron and iron-alloy

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metals, yellow for precious metals, red for base metals, grey for bauxite, violet for energy metals (U) and green for special metals (Ladenberger et al., 2018).

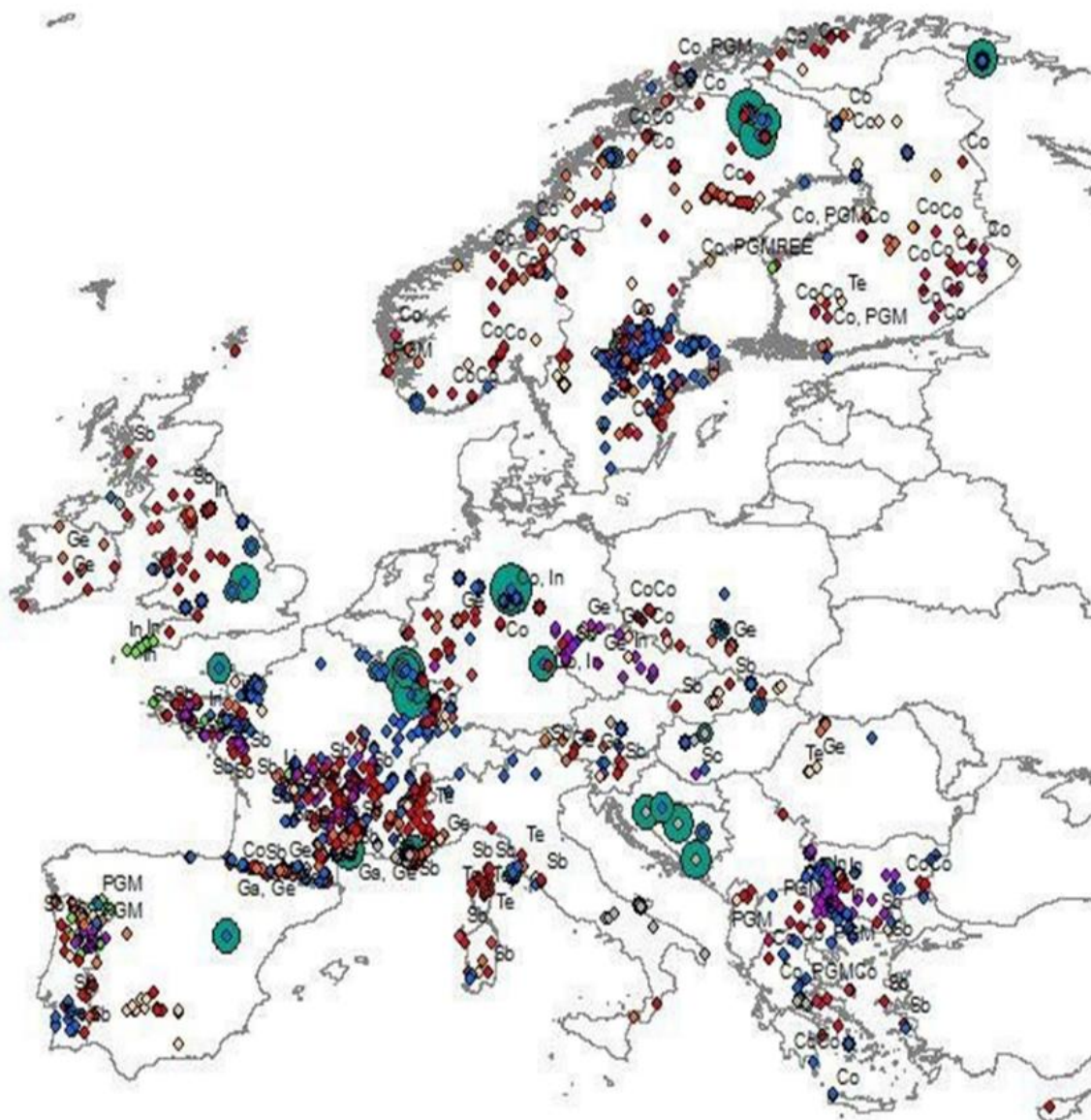


Figure 1: The state of closed mines and active mines in Europe

- establish a European mining legacy database, compare present legal framework, governance structures and management approaches,
- provide input to mine authorities, regulators and financial institutions on a social balanced and environmental-friendly management of mine legacies,
- harmonize best practices, standards and lessons learnt for a comprehensive and sustainable management of raw materials' extraction legacies and
- disseminate the results to the public through an open access visualization platform.

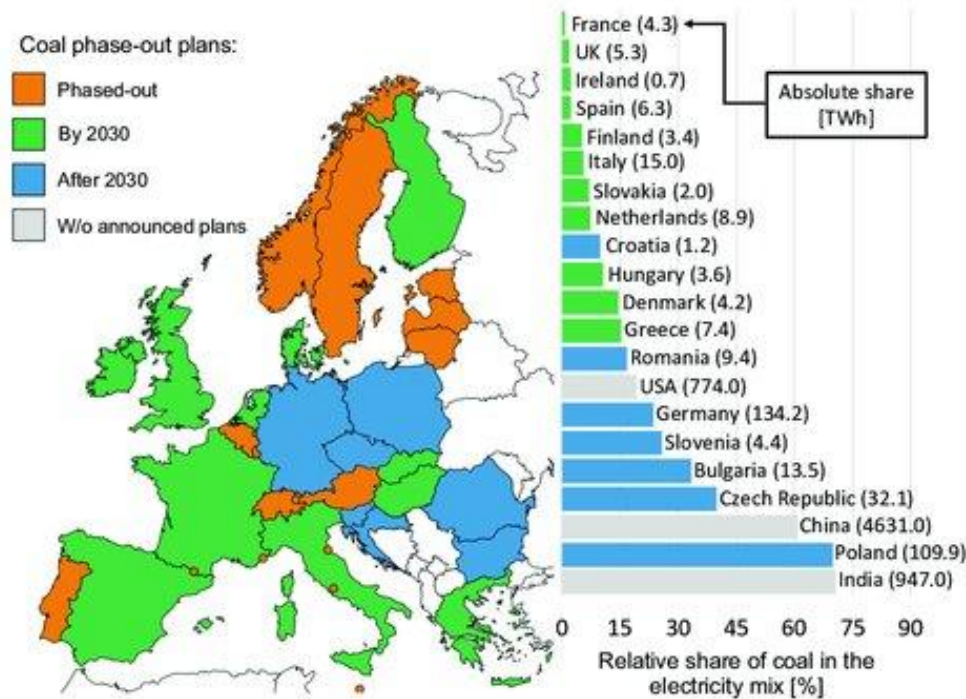


Figure 2: Situation of the coal-phase out in Europe (Debiagi et al, 2022)

The network unites experts from currently separated fields, including geologists, economists, engineers, environmental and social scientists, metallurgists, legal representatives, to consolidate knowledge and foster mutual exchange of knowledge between researchers. These challenges are increasingly being addressed by universities and engineering research centres involved in post-mining issues.

The project is structured into 5 working groups as given in Figure 3. WG 1 focuses on different legislation, governance and management practices across European mining countries. WG 2 addresses socio-economic aspects and the financing of mine legacies. WG 3 focuses on the rehabilitation, monitoring and risk management of the different environmental aspects of raw materials’ extraction legacies. WG 4 concentrates on training and capacity building, while WG 5 handles dissemination, communication, and project management (REMINDNET, 2024).

REMINDNET consist of 5 Working groups:

- WG 1 - Government and management practices
- WG 2 - Socio-economic aspects and financing
- WG 3 - Environmental monitoring and risk management and use of abandoned mines
- WG 4 - Training and capacity building
- WG 5 - Dissemination and communication, Project Management

Figure 3: Structure of REMINDNET project

Working Group 4, serving as the primary focus of this paper, aims to promote and strengthen knowledge related to post-mining management. Its capacity-building activities focuses on developing and strengthening the skills, instincts, abilities, processes and resources that organizations and communities require for post-mining risk assessment and management. Through the support of the REMINDNET network, the project partners organize training schools dedicated to PhD students. Each training school welcomes around 20 selected doctoral candidates and young engineers to attend theoretical and practical courses on post-mining challenges. Participants also have the opportunity to engage with professors and experts involved in post-mining research and development.

In 2024, WG 4 organised the first online workshop with the title of “Good practice in Recovery of Mining Districts”. The event focused mainly on the sustainable transformation of the degraded areas and tailings, as well as multidisciplinary management of mining legacies.

In 2025, the first training school was held in Bochum, Germany, and covered topics related to the latest remediation, rehabilitation, and monitoring techniques applied to raw-material extraction legacies. Two additional training schools are planned for 2026: the first in Italy, focusing on “Legislative and management aspects” and the second in Turkey, addressing “Socio-economic aspects and financing methodologies”. The final training school within the REMINDNET project will take place in 2027 and will thematically address the issues of reclamation, monitoring and geohazards in the post-mining landscape.

3. State of the art

Closing of mining operation involves numerous complex issues, including reclamation and environmental protection, community issues, socio-economic consideration, planning for alternate use of available facilities, cost estimation and asset disposal. Mine closure and post-mining management are a combination of technical know-how and technical skills to successfully complete complex closure projects. Engineers in charge of mine closure and post-mining managements should possess sufficient experience and knowledge to critically analyse both technical and non-technical information.

Furthermore, the mine closure should gather broader information on impacts, risks, and mitigation measures, including stakeholder requirements, needs, and wishes, as well as post-closure land capacity requirements to ensure land adaptability. Mine closure engineers should solve a complex puzzle whose pieces include economic factors, feasibility, long-term sustainability of the closure, operational requirements, and reputation.

They must be able to see all the pieces of the puzzle and facilitate discussions, assess trade-offs, and analyse options to produce a coherent closure strategy. The mine closure integration officer is able to identify whether the objectives of a smaller area, landform, or discipline are inconsistent with other elements. These specialists in mine closure and post-mine management should have solid theoretical and practical expertise to address the complex details of mine closure, ranging from environmental rehabilitation to socio-economic considerations (Boggs et al, 2025).

CRC TiME Project carried out a survey to identify the needs in Australia, and the results highlighted that only 13% of survey participants had detailed knowledge of mine closure planning processes and 17% of participants specified mine closure processes as the most important training need for the mining sector. Participants specified their top three priority areas of skills development as mine closure planning processes, risk assessment, and communication and engagement, including with First Nations communities. The absence of a vocational education and training pathway contributes to this gap. The core skills and knowledge necessary for mine closure extend beyond restoration activities, encompassing governance, operations, and social and economic dimensions. However, currently, mining and post-mining activities are not enough attractive for young researchers and engineers (CSIRO, 2023).

Dejkovski (2024) explored education and training opportunities in Australia. He notes that multidisciplinary areas of expertise required in mine closure and post mine transitions and that no single course is likely to address all noted skill sets. The existing training packages are mostly mining related and not necessarily related to mine closure.

The research of existing education programs highlighted that a limited number of educational programs currently are focused on post-mining topics (Table 1). One such complete program is the master’s degree “Geotechnical Engineering and Post-Mining” offered by University of Applied Sciences Georg Agricola (THGA) in Germany.

Similarly, in the Czech Republic, a study program called “Revitalisation of Post-Mining Landscape” has been newly accredited at the VSB-Technical University of Ostrava, however, lectures are currently held in the Czech language only. At most other European and international universities, only few hours are dedicated to post-mining through seminars and workshops.

Another relevant master’s degree is offered at the Freiberg Mining Academy (TUBAF) in Germany. While, this e master’s program focuses on mine closure rather than post-mining management, it should provide knowledge and skills in the fields of sustainable mining, mine rehabilitation and revitalization (TUBAF, 2026).

The Missouri University of Science and Technology offers a graduate certificate in mine reclamation, providing formalized education for engineers, geologists, and other scientists who work in the field without

any formal training. The program aims to equip these students with the skills that allow them to work as mine reclamation professionals and regulators on mine reclamation projects (Missouri S&T, 2026).

Table 1: Example of education and training courses related to closer and post-mining assessment and management

Name	Location / Language	Website
Geo-engineering and Post-mining (Master Program)	Germany / German	https://www.thga.de/en/degree-programs/overview/geo-engineering-and-post-mining
Sustainable Mining and Remediation Management (Master Program)	Germany / English	https://tu-freiberg.de/en/study/master-sustainable-mining-and-remediation-management https://www2.daad.de/deutschland/studienangebote/international-programmes/en/detail/4446/
Revitalisation of the Post-mining Landscape (Master Program)	Czech Republic / Czech	https://www.hgf.vsb.cz/cs/uchazeci/studijni-programy/bakalarske-studium/?programmeId=1182&academicYearId=66&studyLanguageIds=1
Land Reclamation International Graduate School	Canada / English	https://lrigs.ualberta.ca/
Graduate Certificate in Mine Reclamation	US / English	https://distance.mst.edu/distance-programs/distance-graduate-certificates/mine-reclamation/
Integrated Mine Closure (Course)	Australia / English	https://www.ausimm.com/courses/professional-certificates/integrated-mine-closure
Foundation of Mine Closure and Sustainable Transition (Course)	Australia / English	https://study.uq.edu.au/short-courses/foundations-mine-closure-and-sustainable-transitions
Mining and Environment (Specialized Master)	France / French	https://www.imt-mines-ales.fr/en/specialized-master-mining-and-environment
Sustainable Mining (Master)	France / French	https://www.minesparis.psl.eu/formations/masteres-specialises/ms-industrie-des-ressources-minerales-societe-miris/
Advanced Mineral Resources Development (Master)	Germany, Ukraine, Austria / English	https://cms.nmu.org.ua/en/AMRD/AMRD.php
Mine Closure Fundamental (Course)	Canada	https://community.edumine.com/p/mine-closure-fundamentals/register

Research projects aimed at better planning mine closure and mine site reclamation from the early stages of a mining project life cycle are exposed as possible steps to strive for optimal mine waste management, sustainable reuse of post-mining land and valorisation of the mining waste. The researches focus mainly on ecological restoration evaluation: assessment of ecological restoration quality, evaluation of ecological restoration benefits and the evaluation of ecological restoration measurement methods, primarily centered on the rehabilitation of watersheds, wetlands, and other ecosystems. Certain projects aim to develop tools for satellite remote sensing images, aerial photographs, maps, and other relevant sources, in order to assess ecological restoration, post-mining management, based on the perspective of changes in historical information. Researches also are carried out in the fields of environmental, socio-cultural and economic impacts of mine closure. Also, the feasibility of using UAV–AI–MR (Unmanned Aerial Vehicle – Artificial Intelligence – Mixed reality) technology is one of challenge for monitoring post-mining hazards (Figure 4). A related topic is the assessment of multi-risk in post-mining land and the long-term impact of climate change on the restoration of mining lands including lakes and tailing dams.

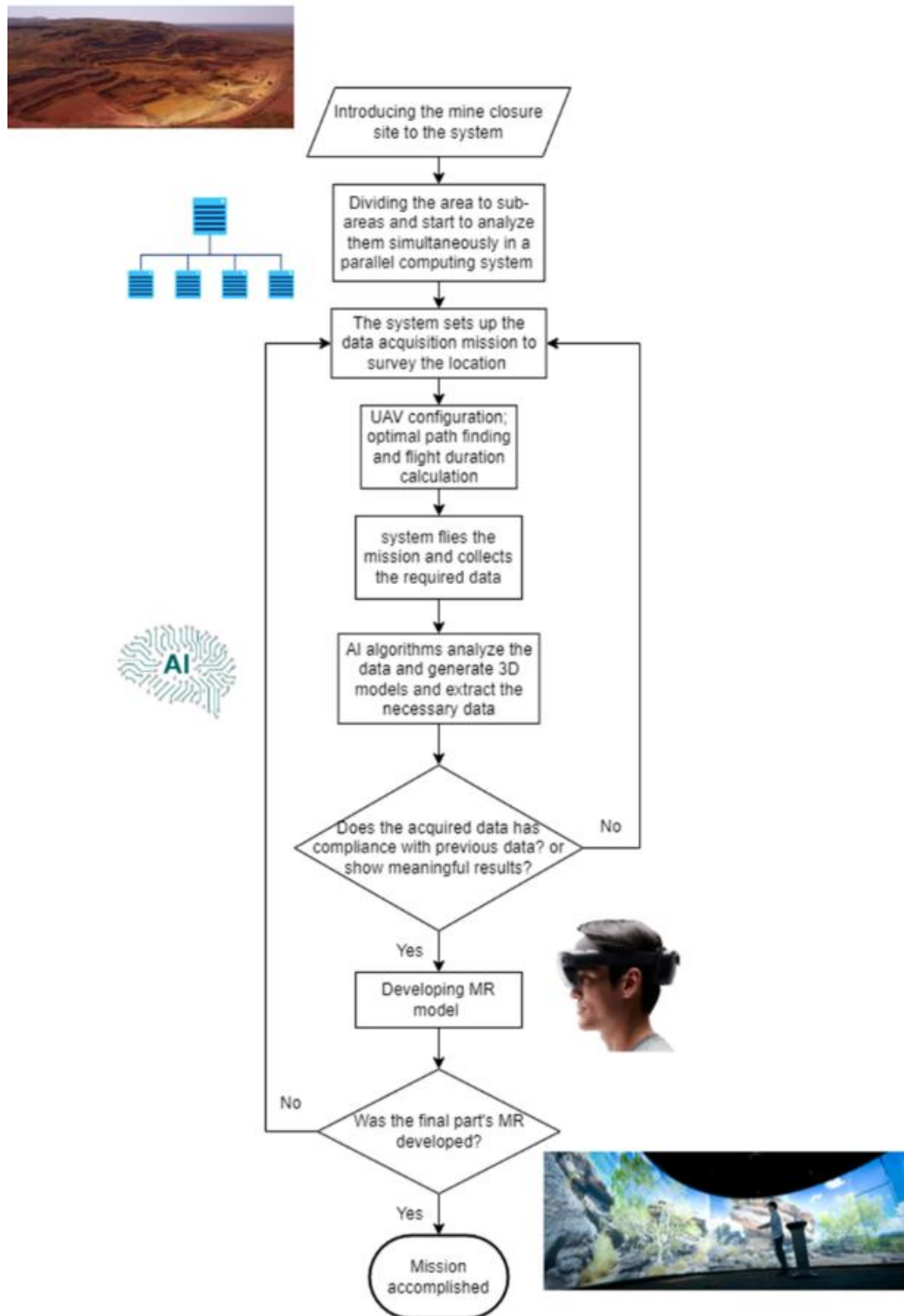


Figure 4: Research carried out of the use of new technologies and AI in the post-mining management and long-term land monitoring (Samaei et al., 2024)

4. First Training School

In 2025, a five-day intensive training school was organised by REMINDNET from June 24 to 28 in Bochum, Germany (Figure 5). The training school addressed the latest remediation, rehabilitation and monitoring techniques and their application on the raw materials' extraction legacies. The participants were from Turkey, the Czech Republic, Finland, Italy, North Macedonia, the UK, Bosnia and Herzegovina, Morocco, Serbia, Bulgaria, France, Estonia and Germany. Numerous partner universities from the network were hosted by the THGA in the Ruhr mining region. Designed for doctoral students and young researchers, the training school presented both proven and innovative methods for the remediation and renaturation of post-mining areas. The program comported, methodologies, case studies, working groups and site visits.

The REMINDNET Training School facilitated an excellent international and practical exchange that looked at post-mining from multiple perspectives and included state-of-the-art technologies (e.g. in geomonitoring) in the program. Participants presented case studies on remote sensing of a post-mining landscape using QGIS and the Google Earth Engine, as well as various drones from the Research Center of Post-mining, which are fundamentally important and versatile technical tools for geomonitoring.

The practical part also included field excursions throughout the Ruhr region to demonstrate the region's transition. The excursion program for the international guests included the German Mining Museum in Bochum, the Ewald Colliery with its current forms of use in the area of local recreation and events, as well as the Nordsternpark in Gelsenkirchen. In addition, the participants worked as a team to develop innovative approaches to the conversion of post-mining landscapes with a focus on practical examples and local value creation.

Overall, the training school proved not only the relevance of the topic (from ecological to social, economic, political and legal aspects of post-mining), but also showed why REMINDNET is so valuable for multinational problem-solving and teaching.



Figure 5: First REMINDNET training school

5. Conclusion

In conclusion, with many mines closure expected in the coming years, it is urgent to construct European education program. Such curricula for undergraduate and post graduate are essential to meet to face the demands in the domain post-mining risk management, remediation and reclamation of post-mining lands.

This paper has shown that education and capacity building in the area of post-mining are very limited, despite the growing number of closed and abandoned mines. The REMINDNET project contributes to enhancing the education of the post-mining and preparing future engineers to effectively address the complex challenges raised by post-mining subjects.

The training schools are organized by the REMINDNET experts and specialists, providing PhD students and young engineers to acquire and apply the knowledge in the study subjects.

Acknowledgments

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Öksüt Madencilik Sosyal Sorumluluk Çalışmaları

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Özet

Öksüt Madencilik A.Ş. Kayseri ili Develi ilçesinde bulunan ve Centerra Gold'a ait Öksüt Altın Madeni İşletmesinde devam eden üretim faaliyetlerine bağlı olarak; sosyal onayı korumak ve güçlendirmek amacıyla "topluma ve çevreye saygılı, sürdürülebilir madencilik" anlayışıyla kurumsal bir Sosyal Yönetim Sistemi uygulamaktadır. Sistem; paydaş katılımı, şikâyet yönetimi, toplum sağlığı ve güvenliği, toplumsal kalkınma, geçim kaynaklarının desteklenmesi ile yerel istihdam ve satın alma uygulamalarını geniş bir çerçevede ele almaktadır. Paydaşlarla kurulan düzenli ve şeffaf iletişim mekanizmaları karar alma süreçlerine entegre edilmekte ve uygulamaların yerel dinamiklerle uyumlu biçimde yürütülmesi sağlanmaktadır. 2014–2025 yılları arasında bölgede 100'ün üzerinde sosyal yatırım projesi gerçekleştirilmiştir. Proje uygulamaları; eğitim, halk sağlığı, kadınların ekonomik katılımı, sportif faaliyetler ile tarım ve hayvancılığın desteklenmesi alanlarında yoğunlaşmaktadır. Eğitim projeleri mesleki ve teknik kapasitenin geliştirilmesine ve eğitim altyapısının güçlendirilmesine odaklanmaktadır. Halk sağlığı uygulamaları koruyucu hizmetler ve sağlık altyapısının desteklenmesini kapsamaktadır. Kadın kooperatiflerine sağlanan destekler yerel üretim kapasitesini artırmayı ve kadınların ekonomiye katılmalarını amaçlamaktadır. Tarım ve hayvancılık projelerinde yenilenebilir enerji sistemleri ve modern ekipman kullanımı teşvik edilerek kırsal üretim yapısının güçlendirilmesi hedeflenmektedir. Bu yaklaşım, sosyal boyutu kurumsal yönetim süreçlerine entegre eden ve bölgesel kalkınmayı destekleyen yapısal bir model sunmaktadır.

Anahtar Kelimeler: Sosyal Yönetim Sistemi, Sosyal Onay, Paydaş Katılımı, Toplumsal Kalkınma, Sürdürülebilir Madencilik

Öksüt Mining Social Responsibility Studies

Abstract

Öksüt Madencilik A.Ş., operating the Öksüt Gold Mine in Develi district of Kayseri province, owned by Centerra Gold, implements a corporate Social Management System based on the understanding of "sustainable mining that respects society and the environment" in order to maintain social licence. The system broadly addresses stakeholder participation, grievance management, community health and safety, community development, livelihood support, local employment and procurement practices. Regular communication mechanisms established with stakeholders are integrated into decision-making processes, ensuring that practices are carried out in a manner consistent with local dynamics. Between 2014 and 2025, over 100 social investment projects were implemented in the region. These projects focus on education, public health, women's economic participation, sports activities, and support for agriculture and livestock farming. Education projects concentrate on developing vocational and technical capacity and strengthening educational infrastructure. Community health practices encompass preventive services and support for health infrastructure. Support provided to women's cooperatives aims to increase local production capacity. The aim is to strengthen the rural production structure by encouraging the use of renewable energy systems and modern equipment in agricultural and livestock projects. This approach offers a structural model that integrates the social dimension into corporate governance processes and supports regional development.

Keywords: Social Management System, Social Licence, Stakeholder Engagement, Community Development, Sustainability

1. Giriş

Öksüt Madencilik tarafından İç Anadolu Bölgesi, Kayseri'nin Develi ilçesi sınırları içerisinde yer alan Öksüt Altın Madeni projesinde Keltepe ve Güneytepe olarak açık ocak madenciliği ve yığın liçi yöntemi ile cevher işlenerek karbon kolonları aracılığıyla dore altın üretimi yapılmaktadır. Öksüt Altın Madeni, Türkiye'de Avrupa İmar ve Kalkınma Bankası (EBRD) tarafından finansman desteği sağlanan ilk madencilik projesidir. Ayrıca bu projede Çevresel Etki Değerlendirmesi (ÇED) raporunun yanında Çevresel ve Sosyal Etki Değerlendirmesi (ÇSED) raporunda tamamlanarak çevresel ve toplumsal etkilerine ilişkin değerlendirme süreçleri şeffaf bir şekilde yürütmüştür. Öksüt Madencilik, ISO 14001:2015 Çevre Yönetim Sistemi ve ISO 45001:2018 İş Sağlığı ve Güvenliği Yönetim Sistemi, ISO 50001 Enerji Yönetim Sistemi ve Uluslararası Siyanür Yönetim Kodu (ICMC) sertifikalarına tam uyumla tamamlayarak üretimine devam etmektedir. Bunların yanında Öksüt Madencilik, Dünya Altın Konseyinin Sorumlu Altın Madenciliği İlkelerini (RGMP) de rehber edinmektedir.



Şekil 1: Keltepe Açık Maden Ocağı

Madencilik sektöründe sosyal onayın sürdürülebilirliği, yalnızca çevresel yükümlülüklerin yerine getirilmesiyle değil, aynı zamanda faaliyet gösterilen bölgelerde ortaya çıkan sosyal ve ekonomik etkilerin sistematik ve ölçülebilir biçimde yönetilmesiyle mümkün olmaktadır.

Bu çalışma, Öksüt Altın Madeni projesi tarafından uygulanan sosyal yönetim sistemi ve kurumsal sosyal sorumluluk yatırım programlarının yapısal özelliklerini, uygulama mekanizmalarını ve sürdürülebilir kalkınma üzerindeki etkilerini analiz etmeyi amaçlamaktadır. Çalışmada, şirketin sosyal onayın koruma ve güçlendirme stratejisi çerçevesinde geliştirdiği paydaş katılımı, şikâyet yönetimi, toplumsal kalkınma ve geçim kaynaklarının iyileştirilmesi uygulamaları ele alınmaktadır.

2. Sosyal Yönetim Sistemi

Sosyal Yönetim Sistemi, işletmenin faaliyetlerinden kaynaklanabilecek sosyal etkilerin öngörülmesi, yönetilmesi ve izlenmesi amacıyla yapılandırılmış kurumsal bir yönetim çerçevesi olarak tanımlanmaktadır. Bu sistem; paydaş katılımı, şikâyet mekanizmaları, toplum sağlığı, güvenliği ve emniyeti, toplumsal kalkınma projeleri, geçim kaynaklarının iyileştirilmesi ile yerel istihdam ve yerel satın alma uygulamalarını tek bir çatı altında birleştirmektedir. Risk değerlendirme süreçleri ve düzenli izleme ile desteklenen bu yapı, sosyal etkilerin azaltılmasını ve olumlu etkilerin artırılmasını hedeflemektedir. Sürekli gelişim ilkesi doğrultusunda uygulanan Sosyal Yönetim Sistemi, kurumsal hesap verebilirliği güçlendiren ve sosyal onayın sürdürülebilirliğine katkı sağlayan stratejik bir yönetim aracı niteliği taşımaktadır. Öksüt Madencilik'in sosyal yönetim sistemi aşağıdaki başlıklardan oluşmaktadır;

- Paydaş Katılımı
- Şikâyet Yönetimi
- Topluluk Sağlığı, Emniyeti ve Güvenliği
- Toplumsal Kalkınma ve Sosyal Sorumluluk Projeleri
- Yerel İstihdam ve Yerel Tedarik

2.1. Paydaş Katılımı

Öksüt Madencilik Paydaş Katılım Prosedürü kapsamında tüm paydaş ilişkilerini yürütmektedir. Bu çerçevede paydaşlar; kamu kurumları, yerel yönetimler, meslek odaları, kooperatifler ve birlikler, mahalle muhtarları, ticari işletmeler, çiftçiler, hayvancılıkla uğraşan haneler, hassas gruplar ve yerel halkı kapsayacak şekilde geniş ve çok katmanlı bir yapı içinde ele alınmıştır. Bu yaklaşım, projenin yalnızca teknik ve ekonomik boyutlarıyla değil, aynı zamanda sosyal yapı ve yerel yaşam pratikleriyle etkileşim içerisinde değerlendirildiğini göstermektedir.

Kamu kurumları; kurumsal Sosyal Sorumluluk uygulamaları kapsamındaki sürecin kurumsal çerçevesini oluşturan temel aktörler olarak konumlandırılmıştır. Yerel yönetimler ve ilgili kamu birimleriyle yürütülen iş birliği mekanizmaları, karar alma süreçlerinin mevzuata uyumlu, şeffaf ve koordineli biçimde yürütülmesini sağlamaktadır. Bu durum, proje faaliyetlerinin kurumsal sürdürülebilirliğini güçlendiren bir unsur olarak değerlendirilmektedir.

Yerel kooperatifler, üretici birlikler ise kırsal kalkınmanın desteklenmesi, tarım ve hayvancılık faaliyetlerinin güçlendirilmesi ve yerel ekonomik kapasitenin artırılması kapsamında stratejik paydaşlar arasında yer almaktadır. İlgili paydaşlarla geliştirilen iş birlikleri, yerel üretim ağlarının güçlendirilmesine, kolektif kapasitenin artırılmasına ve ekonomik faydanın daha dengeli dağılımına katkı sunmaktadır. Böylece paydaş katılımı yalnızca bilgilendirme düzeyinde kalmamakta, bölgesel/yerel kalkınma dinamiklerini destekleyen bir modele dönüşmektedir.

Mahalle muhtarları ve yerel halk, projenin sosyal etkilerini doğrudan deneyimleyen ve geri bildirim mekanizmaları aracılığıyla sürece yön veren temel paydaş grupları olarak ele alınmaktadır. Bu kapsamda düzenli iletişim kanalları, şikâyet ve öneri mekanizmaları ile istişare toplantıları, karşılıklı güvenin tesis edilmesine ve karar alma süreçlerinin kapsayıcı biçimde yürütülmesine olanak tanımaktadır. Çiftçiler ve hayvancılıkla uğraşan haneler ise arazi kullanımı, üretim koşulları ve gelir kaynakları bakımından yüksek etkileşim düzeyine sahip gruplar olarak değerlendirilmekte; bu nedenle söz konusu paydaşların görüş ve beklentileri planlama süreçlerine entegre edilmektedir.

Sonuç olarak paydaş katılımı, proje sürecinin ayrılmaz bir bileşeni olarak kurgulanmış; farklı paydaş gruplarının bilgi, deneyim ve beklentilerinin karar alma ve uygulama aşamalarına dengeli ve kapsayıcı biçimde yansıtılması hedeflenmiştir. Bu yaklaşım, sosyal etkilerin etkin yönetimini destekleyen, kurumsal hesap verebilirliği artıran ve uzun vadeli toplumsal uyumu güçlendiren bir yönetim modeli ortaya koymaktadır.



Şekil 2: Paydaş Katılım Toplantıları

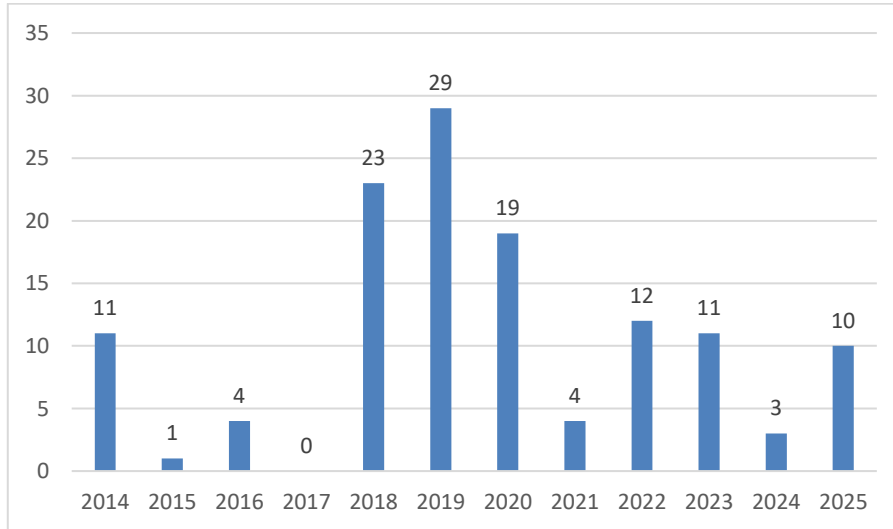
2.2. Şikayet Yönetimi

Öksüt Altın Madeni, faaliyetlerinden etkilenebilecek tüm paydaşlarla açık, saygılı ve güvene dayalı bir iletişim kurmayı kurumsal bir ilke haline getirmiştir. Bu ilke doğrultusunda, hem yerel halka hem de çalışanlara yönelik kapsamlı bir şikayet mekanizması işletilmektedir. Mekanizma; şeffaflık, erişilebilirlik, gizlilik ve zamanında geri bildirim yaklaşımlarıyla yürütülmektedir. Böylelikle toplumun Öksüt Madencilik hakkında bilgi alması, endişelerini iletmesi ve sorunların sistematik biçimde çözülmesi amaçlanmaktadır.

Şikayet mekanizması; yerel topluluklar, muhtarlar, çiftçiler, kooperatifler, STK'lar ve diğer dış paydaşların Öksüt Madencilik ile ilgili görüş, öneri ve şikayetlerini kolaylıkla iletebilmesine imkan sağlayacak şekilde yapılandırılmıştır. Develi ilçe merkezinde bulunan Halkla İlişkiler İrtibat Ofisi, saha ziyaretleri, yazılı başvurular, telefon hattı, e-mail ve projeye komşu mahallelerde ortak alanlara konumlandırılan şikayet ve öneri kutuları, mekanizmanın temel bileşenlerini oluşturmaktadır. Açık Kapı Politikası çerçevesinde paydaşlarla düzenli temas kurulmakta ve saha ziyaretlerinde birebir görüşmeler gerçekleştirilmektedir.



Şekil 3: Halkla ilişkiler irtibat ofisi ve çevre mahallelerdeki şikayet kutusu



Grafik 1. 2014-2025 yılları arası Şikayet adetleri

2.3. Topluluk Sağlığı, Emniyeti ve Güvenliği

Öksüt Madencilik, inşaat ve operasyon süreçlerinde trafik yoğunluğu değişimleri, siyanür kullanımı, güvenlik uygulamaları ve bulaşıcı hastalık riskleri gibi toplumu etkileyebilecek başlıca konulara yönelik olarak; planlama, eğitim, risk değerlendirmesi, acil durum hazırlığı, paydaş bilgilendirmesi, düzenli denetim

ve kayıtların incelenmesi gibi yöntemlerle, ilgili yöneticilerin sorumluluğunda uygulanacak kapsamlı bir halk sağlığı, emniyeti ve güvenliği yönetim yaklaşımını benimsemektedir.



Şekil 4: Evde Güvenlik ve İlk Yardım Projesi (Anneler ve Çocuklar için)

2.4. Toplumsal Kalkınma ve Sosyal Sorumluluk Projeleri

Öksüt Altın Madeni olarak yürütülen sosyal projeler; maden faaliyetlerinin etki alanında ortaya çıkabilecek olumsuz sosyal algı ve etkilerin yönetilmesini, olası olumsuz algıların azaltılmasını ve Develi ilçesi ile sosyal etki alanındaki mahallelerde uzun vadeli toplumsal fayda yaratılmasını hedefleyen sosyal yatırım yaklaşımı çerçevesinde ele alınmaktadır. Bu yaklaşım; eğitim, kırsal kalkınma, sağlık, spor, kültür ve sosyal dayanışma gibi alanlarda kalıcı ve ölçülebilir olumlu değişimler yaratmayı amaçlamaktadır.

Bu çerçevede Öksüt Madencilik'in sosyal projeleri, iki tamamlayıcı eksen etrafında yapılandırılmaktadır.

İlk eksen, maden faaliyetleriyle doğrudan ilişkili olabilecek alanlarda ortaya çıkan etkilerin hafifletilmesine ve iyileştirilmesine yönelik müdahaleleri kapsamaktadır. Bu eksen çerçevesinde mera ve arazi erişim yollarının iyileştirilmesi, su teminine yönelik yatırımlar, karla mücadele uygulamaları ile altyapı ve üstyapı iyileştirme çalışmaları hayata geçirilmekte; günlük yaşamı doğrudan etkileyen konularda somut iyileşmeler sağlanması hedeflenmektedir.

İkinci eksen ise bölgenin yapısal kalkınma ihtiyaçlarına odaklanan sosyal yatırımları içermektedir. Eğitim düzeyinin yükseltilmesi, tarımsal verimliliğin artırılması, hayvancılık kapasitesinin güçlendirilmesi, kadın ve gençlerin üretim ve istihdam süreçlerine katılımının desteklenmesi bu eksenin temel odak alanlarını oluşturmaktadır. Bu doğrultuda modern tarım uygulamaları, suni tohumlama, alternatif yem üretimi, sulama kooperatifi ve güneş enerjisi yatırımları, kadın kooperatifleri ve sürdürülebilir gelir imkanları projeleri gibi uygulamalar hayata geçirilmektedir.

Bunlara ek olarak, şirket-toplum ilişkisini güçlendirmeyi hedefleyen spor faaliyetleri ve sponsorluklar, toplum sağlığı projeleri, kültür ve sanat etkinlikleri, ulusal ve uluslararası sempozyumlara destekler ile Ramazan ve Kurban dönemlerinde yürütülen sosyal yardımlar ve afet sonrası destek çalışmaları, Öksüt Madencilik'in sosyal yatırım portföyünün tamamlayıcı unsurları olarak değerlendirilmektedir. Bu projeler, toplumsal dayanışmayı güçlendirmeyi ve yerel ölçekte güven ilişkilerinin sürdürülmesini amaçlamaktadır.

Bu yönüyle sosyal projeler ile maden faaliyetleri arasındaki ilişki çift yönlü bir yapı sergilemektedir. Bir yandan maden faaliyetlerinden etkilenen alanlarda iyileştirici ve telafi edici uygulamalar hayata geçirilirken, diğer yandan bölgenin uzun vadeli kalkınma ihtiyaçları desteklenmekte ve Öksüt Madencilik'in bölgeyle ilişkisi yalnızca bir işveren olmanın ötesine taşınmaktadır.

Öksüt Madencilik, sosyal projelerini planlarken ve uygularken kamu kurumları, yerel yönetimler, kooperatifler ve özel sektör paydaşları ile iş birliği içinde hareket etmektedir. Bu yaklaşım, sosyal yatırımların yerel ihtiyaçlarla uyumlu, sahiplenilen ve sürdürülebilir yapılar olarak hayata geçirilmesini desteklemektedir. Aynı zamanda projelerin tasarımında, uygulama sürecinin şirket varlığına bağımlı olmaksızın devam edebilmesini sağlayacak kapasite geliştirme, yerel aktörlerin güçlendirilmesi ve kurumsal mekanizmaların oluşturulmasına önem verilmektedir. Bu sayede projelerin etkisinin firma faaliyetlerinden bağımsız olarak da uzun vadede sürdürülmesi hedeflenmektedir. Bu kapsamda uygulanan Toplumsal Kalkınma ve Sosyal Sorumluluk Proje kategorileri aşağıdaki gibidir;

- Halk Sağlığı Projeleri
- Geçim Kaynaklarını İyileştirme ve Kırsal Kalkınma Projeleri
- Eğitim Projeleri
- Sürdürülebilir Gelir Getirici Fırsat Projeleri

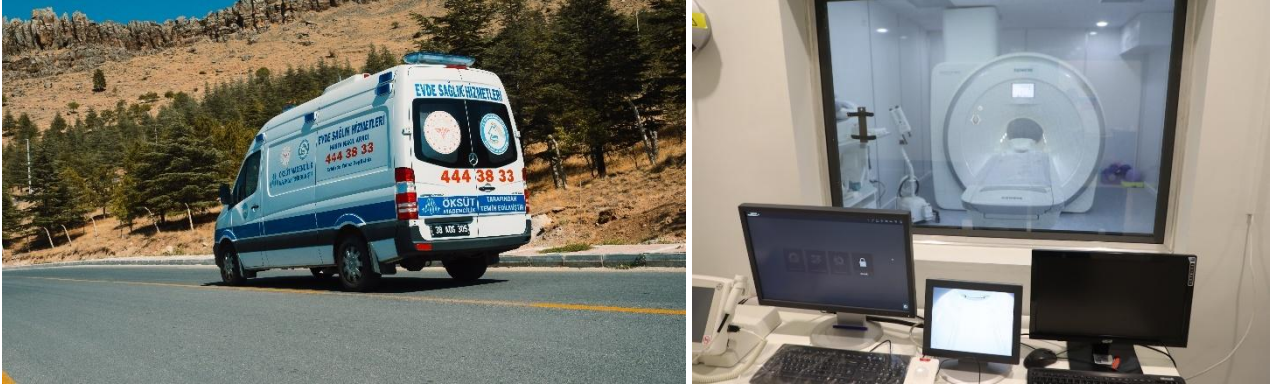
- Altyapı ve Üst Yapı İyileştirme Uygulamaları
- Kültürel ve Sanatsal Faaliyetlerin Desteklenmesi
- Spor Faaliyetlerinin Desteklenmesi ve Sponsorluklar
- Bağışlar

2.4.1 Halk Sağlığı Projeleri

Öksüt Madencilik, bölgede hayata geçirdiği projelerle toplum sağlığının korunması ve geliştirilmesi, sağlık hizmetlerine erişimdeki eşitsizliklerin azaltılması ve özellikle kırılgan grupların yaşam kalitesinin artırılması amacıyla içinde fiziki yatırım da olan sağlık projeleri gerçekleştirmektedir. Projeler koruyucu sağlık uygulamalarından erken tanı kapasitesini büyüten tıbbi cihaz yatırımlarına, evde bakım ve erişilebilirlik çözümlerinden salgın döneminde hızlı müdahale desteklerine uzanan geniş bir etki alanı oluşturmaktadır.

Öksüt Madencilik'in sağlık yatırımları, ilçe ölçeğinde sağlık hizmetlerine erişimi güçlendiren ve sahada doğrudan karşılık bulan somut çıktılar üretmektedir. Develi Devlet Hastanesi tarafından paylaşılan izleme verilerine göre mamografi cihazı, hasta bakım ambulansı, evde bakım aracı, renkli ultrasonografi cihazı ve MR görüntüleme altyapısı yatırımları sayesinde 2017-2025 döneminde toplam 46.926 kişi doğrudan sağlık hizmetlerinden yararlanmıştır. Yararlanıcıların yaklaşık %63'ünü kadınlar oluşturmaktadır. Bu durum özellikle kadın sağlığına ve bakım hizmetlerine yönelik yatırımların sahadaki etkisini açık biçimde ortaya koymaktadır. Develi İlçe Sağlık Müdürlüğü verileri ise filyasyon aracı, aşı dolabı ve vücut analiz cihazı gibi koruyucu sağlık altyapısı yatırımlarından toplam 108.048 kişinin faydalandığını göstermektedir ve bu yararlanıcıların %53'ü kadınlardan oluşmaktadır. Bu bulgular, Öksüt Madencilik'in özellikle salgın döneminde ve sonrasında gerçekleştirdiği sağlık yatırımlarının yalnızca hizmet kapasitesini artırmakla kalmadığını, aynı zamanda kadınlar başta olmak üzere kırılgan grupların sağlık hizmetlerine erişiminde belirgin bir iyileşme sağladığına işaret etmektedir. Bu kapsamda hayata geçirilen proje ve faaliyetler;

- Öğrenciler için Sağlıklı Beslenme, Hijyen, Dış Sağlığı Eğitimleri ve Sağlık Taraması Uygulamaları
- Hasta Yatağı ve Diğer Tıbbi Malzemeler Temini
- Komşu Mahalleler İçin Çöp Konteynerleri Temini
- Diyabet & Obezite Kontrol Programı
- Meme Kanseri ile Mücadele ve Farkındalık Projesi (Mamografi Cihazı Temini)
- Evde Sağlık Hizmetleri Projesi (Hasta Bakım ve Nakil Ambulansı Temini)
- Covid-19 Salgını İle Mücadele Projesi (Filyasyon ve Aşılama Araçları Temini)
- Maske Üretimi Projesi (Öğrenciler, Dez Avantajlı Gruplar, Kamu ve Maden Çalışanları için)
- Evde Güvenlik ve İlk Yardım Projesi (Anneler ve Çocuklar için)
- Öğrenciler için Covid-19, İSG ve Çevre Konulu Farkındalık Eğitimi Projesi
- Engelsiz Yaşamı Destekleme Projesi (Akülü Tekerlekli Sandalye ve Şarj İstasyonu Temini)
- Sağlık Hizmetleri Kapasite Geliştirme Projesi (Renkli Ultrason, Aşı Dolapları, Vucut Analizi Cihazı ve Tefrişat Temini)
- Manyetik Rezonans (MR) Tıbbi Cihaz Bağışı
- Engelsiz Yaşam, Bakım, Rehabilitasyon ve Aile Danışma (Otizm) Merkezi Spor ve Oyun Alanları Oluşturma Projesi
- Kadın Hastalıkları Bilinçlendirme Programları
- Kırsal Mahalleler İçin Kış Koşulları İle Mücadele Ekipman Temini



Şekil 5: Evde Sağlık Hizmetleri Projesi (Hasta Bakım ve Nakil Ambulansı Temini) ve Manyetik Rezonans (MR) Tıbbi Cihazı

2.4.2. Geçim Kaynaklarını İyileştirme ve Kırsal Kalkınma Projeleri

Öksüt Madencilik tarafından Develi’de yürütülen sosyal projeler, tarım ve hayvancılığın temel geçim kaynağı olduğu bölgelerde üretim koşullarının iyileştirilmesi, gelir istikrarının desteklenmesi ve uzun vadeli kırsal sürdürülebilirliğin güçlendirilmesi amacıyla hayata geçirilmiştir. Projeler, maden faaliyetleriyle eş zamanlı olarak bölgenin sosyal ve ekonomik yapısının desteklenmesine yönelik tamamlayıcı uygulamalar olarak tasarlanmıştır. Bunlar altyapı iyileştirmelerinden üretim girdilerine, teknik kapasite geliştirmeden izleme ve değerlendirme mekanizmalarına kadar uzanan çok katmanlı bir yaklaşım çerçevesinde ele alınmıştır.

Bu kapsamda hayata geçirilen proje ve faaliyetler;

- Mera ve Tarım Arazilerine Ulaşım Yolları ve Su Kaynaklarını İyileştirme Projeleri
- Tarımsal Faaliyetleri İyileştirme & Geliştirme Projeleri (Tarımsal Makine & Ekipman Temini)
- Silaj Paketleme Tesisi Projesi
- Kapalı Devre Basınçlı Sulama Projesi
- Arı Yetiştiriciliği Projesi
- Gebe ve Buzağılı Düve Yetiştiriciliği Projesi
- Canlı Hayvan Pazarı Restorasyonu Projesi
- Suni Tohumlama ile Irk Islahı Projesi
- Gelir ve Yaşam Koşullarına Etki İzleme Programı
- TÜBİTAK Mam Lab. da Bal ve Gacer Ürünlerinin Gıda Analizi Uygulamaları
- Hayvan Yetiştiricileri için Bilinçlendirme Eğitimleri (Sürü Yönetimi, Beslenme ve Hayvan Sağlığı)
- Alternatif Yem Üretimi (Flake Yem Fabrikası) Projesi
- Yenilenebilir Enerji Projesi (GES)
- Yeşil Enerjiyle Hayvan İçme Suyu Temini Projesi
- Tarımsal Hayvancılık Faaliyetlerinin Geliştirilmesi ve Desteklenmesine Yönelik Uygulamalar
- Yeşil Enerjiyle Hayvan İçme Suyu Temini Projesi-2 Faz



Şekil 6: Arı Yetiştiriciliği Projesi ve Kapalı Devre Basınçlı Sulama Projesi

2.4.3. Eğitim Projeleri

Eğitim alanındaki sosyal yatırımlar, Develi ilçesinde akademik başarının artırılması, mesleki beceri kazanımının desteklenmesi, doğru kariyer planlama süreçlerine katkı sunulması ve sosyal-kültürel gelişimin güçlendirilmesi hedefleri etrafında kurgulanmıştır. Bu kapsamda yürütülen projeler, eğitimi bireysel gelişimin yanı sıra toplumsal kalkınmanın temel bileşenlerinden biri olarak ele alan yaklaşımla tasarlanmıştır. Eğitim yatırımlarının odak hedef gruplarını ilköğretim ve lise öğrencileri, meslek lisesi ve üniversite öğrencileri, kız öğrenciler, öğretmenler ve genç sporcular oluşturmaktadır. Bu gruplara yönelik geliştirilen faaliyetlerle fırsat eşitliğinin güçlendirilmesi, bireysel potansiyelin ortaya çıkarılması ve uzun vadeli sosyal fayda yaratılması amaçlanmaktadır.

Şirketin Toplumsal Kalkınma Planı doğrultusunda, bölgede yer alan eğitim tesislerinin desteklenmesi ve geliştirilmesine ek olarak, madencilik faaliyetleriyle ilişkili konular, sürdürülebilir kalkınma, çevresel farkındalık, trafik güvenliği ve kişisel gelişim başlıklarında yürütülen bilinçlendirme programları da eğitim destek projelerinin ayrılmaz bir parçası olarak değerlendirilmektedir.

Öksüt Madencilik çevresel ve sosyal farkındalığın artırılmasına yönelik bu çalışmaların yalnızca maden faaliyetlerinin etkilerinin yönetilmesi açısından değil, aynı zamanda proje alanı çevresinde yaşayan komşularının günlük yaşam kalitesinin artırılması ve toplumsal dayanıklılığın güçlendirilmesi açısından da kritik öneme sahip olduğuna inanılmaktadır. Öksüt Madencilik hayata geçirdiği projelerle 18.887 öğrenciye ulaşmıştır. Bu kapsamda hayata geçirilen proje ve faaliyetler;

- Trafik Bilinçlendirme Eğitimleri
- Çevre Bilinçlendirme Eğitimleri (Geri Dönüşüm, Enerji Tasarrufu)
- Robotik Kodlama (STEM) ve Eğitici Zekâ Oyunları Projesi
- BESYO (Beden Eğitimi ve Spor Yüksekokulu) Eğitim Akademisi Projesi
- Maden Teknolojileri Bölümü Projesi (Meslek Lisesi- Maden Teknolojileri Bölümü Açılması)
- Mesleki Eğitimi Geliştirme Projesi
- Kayseri Üniversitesi Develi Yerleşkesine Sosyal Alan Oluşturma Projesi
- Bölgedeki Eğitim Tesisleri Destekleme Projeleri (P.C. Kocatürk Ortaokulu Spor Salonu)
- Develi Akademik Gelişim ve Başarı Projesi
- Bağımlılık Farkındalık Eğitimleri (Yeşilay)
- Bireysel ve Sosyal Gelişim Uygulamaları
- Yenilikçi Mesleki Eğitimler, Kariyer Planlama ve Sosyal Gelişim Projesi
- Sportif Gelişim ve Başarı Projesi
- ERVA Gençlik Merkezi Oluşturma Projesi
- İklim Değişikliği Farkındalık Organizasyonu
- Kadın Girişimciler için Sıfır Atık Eğitim Programı
- Akademik Başarı, Kariyer Planlama, Teknolojik ve Sosyal Gelişim Projesi
- Doregi Çocuk Tiyatrosu Etkinlikleri (Kırsal Mahalleler, Develi İlçe Merkezi, Deprem Bölgesi)



Şekil 7: Akademik Başarı, Kariyer Planlama, Teknolojik ve Sosyal Gelişim Projesi ile Teknofest Başarısı

2.4.4. Sürdürülebilir Gelir Getirici Fırsat Projeleri

Bölgede yürütülen kadınlara yönelik sürdürülebilir gelir imkanları projeleri, çevresel, sosyal ve ekonomik açıdan uzun vadeli fayda yaratmayı hedefleyen toplumsal kalkınma yaklaşımının bir parçası olarak kurgulanmıştır. Bu projeler; yerel kaynakları ve mevcut yetkinlikleri dikkate alarak, kadınların istikrarlı gelir elde edebileceği, üretim ve hizmet odaklı iş modellerinin geliştirilmesini amaçlamaktadır.

Söz konusu yaklaşım, proje başlangıcından itibaren benimsenmiş; Develi ilçesinde yürütülen saha çalışmaları, bilgilendirme faaliyetleri ve paydaş görüşmeleri aracılığıyla bölgenin sosyo-ekonomik yapısı, geçim kaynakları ve toplumsal ihtiyaçları düzenli olarak izlenmiştir. Bu süreçte, yerel topluluklarla yürütülen sürekli iletişim sayesinde kadınların üretim, istihdam ve ekonomik hayata katılım alanlarında karşılaştıkları ihtiyaçlar daha net biçimde ortaya konulmuştur.

Öksüt Madencilik Halkla İlişkiler ekipleri, maden arama ve fizibilite dönemlerinden itibaren Develi ilçesinde sahada aktif olarak yer almış; muhtarlar, köy azaları, ihtiyar heyetleri ve diğer yerel aktörlerle gerçekleştirilen görüşmeler yoluyla nüfus yapısı, ekonomik faaliyetler, sosyal hizmetlere erişim ve yerel beklentiler gibi konularda düzenli bilgi akışı sağlamıştır. Bu saha çalışmaları, sürdürülebilir gelir getirici projelerin yerel bağlamla uyumlu ve uygulanabilir şekilde tasarlanmasına temel oluşturmuştur.

Bu çerçevede geliştirilen kadın odaklı projeler, kısa vadeli destek mekanizmaları olarak değil; kadınların üretim kapasitelerini güçlendiren, pazara erişimlerini kolaylaştıran ve kolektif yapılar aracılığıyla ekonomik hayata kalıcı katılımlarını destekleyen sosyal yatırımlar olarak ele alınmaktadır. Kadınların mevcut becerilerinin gelir getirici faaliyetlere dönüşmesini hedefleyen bu projeler, aynı zamanda yerel ekonominin çeşitlenmesine ve toplumsal kalkınmanın güçlenmesine katkı sunmaktadır. Aşağıda sunulan projeler, Öksüt Madencilik'in sürdürülebilir gelir imkanları yaklaşımı doğrultusunda kadınların ekonomik hayata katılımını destekleyen, birbirini tamamlayan ve uzun vadeli etki yaratmayı hedefleyen uygulamalar olarak değerlendirilmiştir. Bu kapsamda hayata geçirilen proje ve faaliyetler;

- Kadın Üreticileri İçin Yöresel Ürünler Pazarı Projesi
- Kadın Üreticileri Geliştirme Projesi (Kadın Üreticiler Koop.-Gacer Kafe)
- Develi Kadın Girişimi Üretim ve İşletme Kooperatifi (Gacer Cafe) Hizmet Kapasitesi Geliştirme Çalışmaları
- Halk Eğitim Bünyesinde Faaliyet Gösteren Kadın Kursiyerler ile İş Birliği ve Üretim Çalışmaları



Şekil 8: Kadın Üreticileri Geliştirme Projesi (Kadın Üreticiler Koop.-Gacer Kafe) ve Halk Eğitim Bünyesinde El İşi Üretim Çalışmaları

2.4.5. Altyapı ve Üst Yapı İyileştirme Uygulamaları

Hayata geçirilen altyapı ve üstyapı iyileştirme uygulamaları, yerel toplulukların günlük yaşam koşullarını doğrudan iyileştirmeyi hedefleyen, hızlı ve somut etki üreten sosyal müdahaleler olarak ele alınmaktadır. Bu projeler; kamusal alanların işlevselliğinin artırılması, temel altyapı hizmetlerine erişimin iyileştirilmesi ve sosyal yaşamı destekleyen mekansal düzenlemelerin hayata geçirilmesi yoluyla toplumsal kalkınmaya katkı sağlamayı amaçlamaktadır.

Altyapı ve üstyapı odaklı bu çalışmalar, özellikle kırsal yerleşimlerde toplulukların kısa sürede fark edilebilir iyileşmeler görme beklentisine yanıt veren uygulamalar olarak tasarlanmıştır. Görünür ve hızlı sonuç üreten bu projeler, yerel düzeyde güven ilişkilerinin güçlenmesine, kamusal alanların daha etkin kullanılmasına ve yaşam memnuniyetinin artmasına katkı sunmaktadır.

Projelerin belirlenmesi ve uygulanması sürecinde yerel ihtiyaçlar temel alınmış; bu kapsamda muhtarlar, ihtiyar heyetleri ve ilgili yerel paydaşlarla yürütülen görüşmeler doğrultusunda öncelikli müdahale alanları tespit edilmiştir. Altyapı ve üstyapı iyileştirme uygulamaları, belirli bir hedef grubun ötesinde, yerleşim yerlerindeki tüm topluluğa hitap edecek şekilde planlanmış ve hayata geçirilmiştir.

Öksüt Madencilik, bu projeleri tek seferlik müdahaleler olarak değil; yerel yönetimlerin ve toplulukların mevcut kapasitesini destekleyen, kamusal alanları güçlendiren ve günlük yaşamı kolaylaştıran tamamlayıcı sosyal yatırımlar olarak değerlendirmektedir. Yol, su, sosyal alan, spor tesisleri ve ortak kullanım alanlarına yönelik uygulamalar, fiziksel çevrenin iyileştirilmesinin yanı sıra sosyal etkileşimi teşvik eden ve topluluk bağlarını güçlendiren bir etki alanı yaratmaktadır.

Aşağıda sunulan altyapı ve üstyapı iyileştirme projeleri, Öksüt Madencilik'in yerel ihtiyaçlara duyarlı, hızlı uygulanabilir ve geniş toplumsal fayda üretmeyi hedefleyen sosyal yatırım yaklaşımı doğrultusunda hayata geçirilen tamamlayıcı uygulamalar olarak ele alınmaktadır. Bu kapsamda hayata geçirilen proje ve faaliyetler;

- Çamlık Mesire Alanı Sosyal Alan Oluşturma Projesi
- Gazi ve Gömedi Mahallerinde Ağaçlandırma ve Sosyal Alan Oluşturma Projesi
- Ortak Alan İyileştirme Tadilat ve Tefrişat Bağışı Uygulamaları
- İçme Suyu Temini Projeleri
- Komşu Mahallelerde Yürütülen Çalışmalara İş Makinası ve Ekipman Desteği
- Spor Tesisleri Oluşturma Uygulamaları
- Alt ve Üst Yapı İyileştirme Uygulamaları
- Asfalt Plenti Tesisi Projesi
- Grup Yolu (Ayvazhacı-Yazıbaşı-Gömedi-Epçe) Projesi
- Proje Komşu Mahallerde Güvenlik Kamerası Uygulamaları
- Komşu Mahallerde Ortak Kullanım Alanları İyileştirme Uygulamaları
- Eğitim Kurumları İçin Spor Tesisleri Oluşturma Projesi
- Köşkpınar-Elbiz Yeşil Enerji ve Sosyal Tesisler Projesi
- Develi Modern Halk Kütüphanesi Projesi



Şekil 9: Spor Tesisleri Oluşturma Uygulamaları, Çamlık Mesire Alanı Sosyal Alan Oluşturma Projesi

2.4.6. Kültürel ve Sanatsal Faaliyetlerin Desteklenmesi

Öksüt Madencilik tarafından desteklenen kültürel ve sanatsal organizasyonlar, yerel toplulukların sosyal yaşama katılımını artırmayı, ortak değerler etrafında buluşmayı teşvik etmeyi ve kültürel erişimi güçlendirmeyi amaçlayan tamamlayıcı sosyal yatırımlar olarak ele alınmaktadır. Bu kapsamda hayata geçirilen faaliyetler; kültürel mirasın korunması, sanata erişimin yaygınlaştırılması, toplumsal dayanışmanın desteklenmesi ve farklı yaş gruplarının sosyal yaşam içinde daha görünür hale gelmesi gibi çok boyutlu hedefleri içermektedir.

Kültürel ve sanatsal organizasyonlar, özellikle günlük yaşamın yoğunluğu ve mekansal kısıtlar nedeniyle kültür-sanat faaliyetlerine erişimi sınırlı olan gruplar için kapsayıcı ve erişilebilir bir sosyal etkileşim alanı yaratmaktadır. Festival organizasyonları, anma ve kutlama programları, kültürel geziler, tiyatro ve sinema etkinlikleri gibi uygulamalar; ilçe merkezi ile kırsal mahalleler arasında kültürel yaşama katılım farklarının azaltılmasına katkı sunmaktadır. Bu faaliyetler, yalnızca etkinlik bazlı müdahaleler olarak değil; sosyal bağları güçlendiren, toplumsal aidiyet duygusunu besleyen ve ortak hafızayı canlı tutan sosyal etkileşim araçları olarak değerlendirilmektedir.

Bu çerçevede kültürel ve sanatsal organizasyonlar, Öksüt Madencilik'in şirket-toplum ilişkisini güçlendirmeye yönelik yaklaşımının önemli bir bileşenini oluşturmakta, farklı paydaş gruplarını bir araya getiren kapsayıcı bir sosyal temas zemini sunmaktadır. Bu kapsamda hayata geçirilen proje ve faaliyetler;

- Uluslararası Aşık Seyrani Kültür ve Sanat Festivalleri Sponsorluğu
- Öğrenciler İçin Sinema ve DOREGİ Tiyatro Günü Etkinlikleri – Milli Bayram Organizasyonları
- Çanakkale Kültür Turu Programı
- İftar Yemeği Yardımlaşma ve Dayanışma Organizasyonları
- Deprem Bölgelerinde Yaşayan Çocuklar için Doregi Çocuk Tiyatrosu Etkinlikleri
- Cumhuriyetin 100. Yılı Kutlama Etkinlikleri Programı
- Depremzede Sanatçılar ve Aileleri İçin Destek Konseri Organizasyonu (Antakya Medeniyetler Korusu)
- 19 Mayıs Atatürk'ü Anma, Gençlik ve Spor Bayramı Kutlama Organizasyonları
- Dünya Çevre Günü Kutlama Organizasyonu
- Erciyes Üniversitesi Çocuk Hematoloji ve Onkoloji Hastanesi'nde 23 Nisan Kutlama Programı
- Kırsal Mahallelerde Sinema Günleri Organizasyonu



Şekil 10: Uluslararası Aşık Seyrani Kültür ve Sanat Festivalleri Sponsorluğu

2.4.7. Spor Faaliyetlerinin Desteklenmesi ve Sponsorluklar

Öksüt Madencilik tarafından yürütülen spor faaliyetlerinin desteklenmesi ve sponsorluk uygulamaları, Develi ilçesinde çocuklar, gençler ve sporcular başta olmak üzere farklı yaş ve sosyal grupların spor yoluyla sosyal hayata katılımını artırmayı, sağlıklı yaşam alışkanlıklarının gelişimini desteklemeyi ve yerel spor ekosisteminin güçlendirilmesini amaçlamaktadır. Bu kapsamda hayata geçirilen projeler, yalnızca sportif başarıyı teşvik eden destekler olarak değil; aynı zamanda gençlerin sosyal gelişimini, özgüven kazanımını ve toplumsal aidiyet duygusunu güçlendiren tamamlayıcı sosyal yatırımlar olarak ele alınmaktadır.

Spor alanındaki sosyal yatırımlar, Öksüt Madencilik'in toplumsal kalkınma yaklaşımı doğrultusunda kapsayıcılık, süreklilik ve yerel ihtiyaçlara duyarlılık ilkeleri temelinde yapılandırılmıştır. Bu çerçevede

destekler; yerel spor kulüpleri, okul takımları ve altyapı ekiplerinin yanı sıra bireysel sporcuları ve farklı branşlarda faaliyet gösteren gençleri kapsayacak şekilde geniş bir hedef grubu içermektedir. Sponsorluk uygulamaları, sporun birleştirici ve dönüştürücü gücünden yararlanarak özellikle genç nüfusun sağlıklı ve üretken bir yaşam sürmesine katkı sunmayı hedeflemektedir.

Bu çerçevede spor faaliyetlerinin desteklenmesi ve sponsorluk uygulamaları, Öksüt Madencilik'in sosyal yatırım portföyü içinde, uzun vadeli sosyal etki üretme potansiyeline sahip bir müdahale alanı olarak ele alınmaktadır. Bu kapsamda hayata geçirilen proje ve faaliyetler;

- Yerel Takım Sponsorlukları (Voleybol, Futbol, Altyapı, Okul Takımları)
- Maden Sektörü Etkinlik Sponsorlukları
- Sportif Gelişim Başarı ve Tüm Spor Faaliyetleri Sponsorluk Uygulamaları



Şekil 11: Yerel Takım Sponsorlukları (Voleybol, Futbol, Altyapı, Okul Takımları)

2.4.8. Bağışlar

- Ramazan ve Kurban Bayramı Yardımlaşma Organizasyonları
- Ortak Kullanım Alanları İçin Kullanım Dışı Yakacak Ahşap Bağışı Uygulamaları
- Deprem Yardım ve Bağış Organizasyonları



Şekil 12: Deprem Yardım ve Bağış Organizasyonları



Şekil 13: Ramazan ve Kurban Bayramı Yardımlaşma Organizasyonları

3. Yerel İstihdam ve Yerel Tedarik

Öksüt Madencilik, faaliyet gösterdiği bölgenin sosyal ve ekonomik kalkınmasına katkı sağlamayı kurumsal öncelikleri arasında konumlandırmaktadır. Bu doğrultuda işe alım süreçleri; şeffaf, erişilebilir ve yerel toplulukları öncelleyen bir sistematik çerçevede yürütülmektedir. Açık pozisyonlar öncelikli olarak yerel gazeteler aracılığıyla duyurulmakta; aday başvuruları özgeçmiş ve standart başvuru formları üzerinden toplanarak Halkla İlişkiler birimi aracılığıyla İnsan Kaynakları departmanına iletilmektedir. İşletme sahasında yaklaşık 1.400 kişiye istihdam sağlanmakta olup, iş gücünün yaklaşık %80'i Kayseri ve Develi bölgesinde ikamet eden yerel nüfustan oluşmaktadır. Bu yapı, bölgesel kalkınma hedefleriyle uyumlu bir istihdam politikasının göstergesi olarak değerlendirilmektedir.

Şirket, yerel ekonominin güçlendirilmesini destekleyen bir tedarik zinciri stratejisi benimsemektedir. Bu kapsamda tedarik süreçleri, mümkün olan durumlarda yerel işletmeleri önceliklendirecek şekilde yapılandırılmaktadır. Kayseri'de faaliyet gösteren küçük ve orta ölçekli işletmelerle kurulan doğrudan iş birlikleri aracılığıyla bölgesel ekonomik kapasitenin artırılması ve istihdam olanaklarının desteklenmesi amaçlanmaktadır. Bu yaklaşım, yerel değer zincirinin güçlendirilmesine yönelik planlı ve bütüncül bir kurumsal uygulama olarak konumlandırılmaktadır.

4. Sonuçlar

Bu çalışma, Öksüt Madencilik tarafından Develi'de yürütülen Öksüt Altın Madeni projesi kapsamında geliştirilen Sosyal Yönetim Sistemi ve sosyal yatırım uygulamalarını değerlendirmiştir. Bulgular, madencilik faaliyetlerinde sürdürülebilirliğin yalnızca ekonomik performansla sınırlı olmadığını; sosyal etkilerin öngörülmesi, izlenmesi ve yönetilmesine dayalı kurumsal bir çerçevenin belirleyici olduğunu göstermektedir. Paydaş katılımı, şikâyet yönetimi, topluluk sağlığı ve güvenliği, geçim kaynaklarının desteklenmesi ve yerel istihdam uygulamalarını entegre eden yapı; risk temelli, ölçülebilir ve hesap verebilir bir sosyal etki yönetimi modeli ortaya koymaktadır.

Sosyal yatırım stratejisinin hem faaliyet kaynaklı etkilerin iyileştirilmesine hem de bölgenin uzun vadeli kalkınma ihtiyaçlarının desteklenmesine odaklanan çift yönlü yapısı dikkat çekmektedir. Sağlık, eğitim, kırsal kalkınma ve kadınların ekonomik hayata katılımına yönelik projeler; yerel kapasiteyi güçlendiren, sosyal dayanıklılığı artıran ve şirket-toplum ilişkisini çok aktörlü bir iş birliği modeline dönüştüren uygulamalar olarak öne çıkmaktadır. Sonuç olarak bu örnek, madencilik sektöründe sosyal onayın sürdürülebilirliğinin; katılımcılık, şeffaflık ve kurumsal entegrasyon temelinde geliştirilen sistematik sosyal yönetim yaklaşımlarıyla mümkün olduğunu ortaya koymaktadır.



Ethnography in Mine Closure Planning: Managing Social Risk and Strengthening Social License to Operate in Türkiye

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Abstract

Today, mine closure processes are primarily treated as activities limited to technical and environmental contexts, focusing on rehabilitation, decommissioning, and regulatory compliance. However, closure is also a social process that reshapes livelihoods, institutions, regional relations, and the legitimacy of future mining projects. This article argues that ethnography, which examines and explains social realities with its unique qualitative research techniques, should occupy a more central place in mine closure planning. Ethnography, particularly through participant observation and "thick description," can reveal social dynamics that technically focused closure models and standard participation tools often fail to capture. In this context, this study develops a theoretically grounded and application-oriented argument for integrating ethnography into closure planning in Türkiye, drawing on research on the social aspects of mine closure in different geographies, mining anthropology, and social impact assessment. The article has three main claims: First, mine closure should be understood not only as the end of production but also as a social and political event. Secondly, the discipline of anthropology offers a particularly strong analytical perspective on mine closure processes because it focuses on social and cultural contexts that may be overlooked in such processes. Thirdly, ethnographic techniques can be transformed into closure-related outputs through three different operational entry points: social closure reference points and criteria, stakeholder and land-use scenarios, and early warning and adaptive management during demobilization. The article also proposes a methodological design for closure planning based on ethnographic information and places this proposal within the Turkish mining context, where the legacy of past closures shapes today's social licence. The article concludes that ethnography can make closure planning more reliable, contextually sensitive, and socially equitable, while also improving risk identification and interdisciplinary decision-making.

Keywords: Ethnography, Mine closure, Social Impact Assessment (SIA), Social License to Operate (SLO), Social risk, Türkiye

1. Introduction

The "mine closure" process, considered the final stage of a mining project, is technically associated with decommissioning, rehabilitation, accountability management, and regulatory compliance (Laurence, 2006; ICMM, 2019). Within this framework, closure is generally treated as a matter of engineering competence, with focus on issues such as slope stability, waste control, water monitoring, infrastructure decommissioning, and post-closure landforms meeting approved criteria. While these considerations are undoubtedly crucial, the fact that mine closure is also a socially transformative process that reshapes livelihoods, re-engines political relations, redistributes uncertainty, and leaves behind environmental legacies that profoundly affect the legitimacy of future mining operations is often overlooked in practice (Bainton & Holcombe, 2018; Owen & Kemp, 2018).

Although this aspect is increasingly addressed in the literature on closures, it is also true that the social dimensions of mine closures are still underdeveloped compared to their technical and environmental dimensions. Bainton and Holcombe (2018) show that the current knowledge, practical guidelines, and institutional capacity regarding the social aspects of closures lag significantly behind the resources allocated

to physical rehabilitation and environmental management. While closure expertise is largely concentrated in technical areas, equivalent competence remains unbalanced in areas such as workforce transition, post-mining economies, stakeholder engagement, infrastructure continuity, housing, and long-term social futures. Similarly, Demajorovic et al. (2022) state that although social awareness is increasingly rising on closures, the environmental technical perspective still remains dominant, and social issues have only recently begun to receive attention.

This imbalance has both analytical and practical consequences. Analytically, it reinforces an event-oriented and technocratic understanding of closure as the controlled closure of mining. Practically, it encourages the treatment of social concerns as a secondary, subordinate, or retrospective issue. Thus, social issues are often included in planning only through limited procedural consultation processes or general and generic socio-economic definitions, rather than through sustainable efforts to understand how mining intermingles with household economies, regional perceptions, political authority, care burdens, informal exchange, and perceptions of justice (Finucane, 2008; Owen & Kemp, 2018; Vanclay et al., 2015). As a result, a persistent disconnect emerges between the technical performance of closure and the social outcomes of closure (Bainton & Holcombe, 2018; Everingham et al., 2020).

This disconnect has significant consequences, particularly in contexts where mining projects are already the subject of societal debate. In Türkiye, the most significant constraint on mining activities in recent years has been a lack of social acceptance rather than physical or technical problems. Social acceptance has become one of the most important conditions determining the feasibility of mining projects. Although this issue is often addressed through the concept of "social license to operate" (SLO), this concept is still often limited to the processes by which mining operations commence (Prno & Slocombe, 2012; Demajorovic et al., 2022). However, society does not evaluate mining projects solely based on existing benefits or current interactions. Social acceptance also has a significant impact on evaluation and perception. Mining activities alone, along with other investments in the surrounding area, form a cumulative impact that shapes the social experience. The cumulative impacts of previous experiences, like unemployment, incomplete rehabilitation, unmet compensation expectations, damaged livelihoods, and distrust of companies and institutions, become part of the perceptual framework when evaluating new projects (Bainton & Holcombe, 2018; Owen & Kemp, 2018). Therefore, closure is not contextually limited to the post-mining period. Rather, the management of this process includes the period preceding the closure activities, and even, considering the cumulative effect, the processes leading up to the commencement of operational activities.

Before managing the process of mine closure, it is necessary to detail the social structure and relationships, and to determine a roadmap based on analyses of these outputs in order to understand the existing social and cultural structure. In this process, conducting social research in the field of mining's social impact is essential.

Social anthropology is the study of human societies, cultures and social life. Social anthropologists have long emphasized that mining processes are not only technical and economic interventions, but also political, moral, ecological, and cultural transformations (Ballard & Banks, 2003; D'Angelo, 2015; Golub, 2019). Experiences in the social impact assessment (SIA) processes of hydroelectric power plant projects (HEPPs) in Türkiye show that when companies and state institutions evaluate social opposition in a narrow context, solely within the framework of security or social engineering, the result is often a social conflict (Özkan, 2014). However, evaluating social opposition from a holistic perspective allows for a better understanding of the existing dynamics in society. Ethnography, a qualitative research method including deep, firsthand study of cultures, societies or social groups, being the most important methodological approach of social anthropology, possesses a unique tool for identifying lived, relational, and often "deep-seated" social and cultural relationships and structures that are often overlooked by standard research tools.

In this context, the focus of this article is not only to advocate for a more "social" closure planning approach in general, but also to demonstrate that the necessary input for this planning can be obtained more comprehensively and holistically through ethnography. The article has four objectives. First, to show why mine closure should be conceptualized not only as a technical process, but also as a social and political process. Second, to strengthen the anthropological foundations of the argument by drawing on mining anthropology, applied anthropology, and ethnographic studies on mining industries. Third, to propose a methodological framework for closure-focused ethnographic research. Fourth, to offer a framework for applying this approach in Türkiye in a way that is sensitive to both academic debates and the practical demands of closure planning.

2. Theoretical Background

2.1. Mine Closure Beyond Technical End-of-Life Models

A large part of the current literature on closure consists of engineering, environmental remediation, and regulatory design issues (Laurence, 2006; ICMM, 2019). As a result of decades, even centuries, of mining experience, it is natural that tools for physical rehabilitation, closure cost estimation, decommissioning, monitoring, and relinquishment are relatively advanced. On the other hand, the social aspects of closure are weakly institutionalized and theorized in an unbalanced way, and today the social cost of mine closure is becoming increasingly important for the overall sustainability of mining operations. Bainton and Holcombe (2018) show that the development of standards, guidelines and policy tools related to the social aspects of closure is still in an early stage, and that universal standards and principles have not yet been fully reflected in practice, revealing a clear asymmetry between the depth of the literature on physical closure and the relative weakness of the literature on social closure. Demajorovic et al. (2022) similarly show that social issues have only recently come to the forefront, and even then, environmental perspectives continue to dominate.

This asymmetry reflects a deeper structural logic inherent in mining governance. In this logic, the mine closure process is primarily perceived as a technical end-of-life issue (Bainton & Holcombe, 2018; Owen & Kemp, 2018). Even when social issues are acknowledged, they are generally treated as a layer to be added to an already established closure plan. Bainton and Holcombe (2018) note that companies tend to add social considerations to existing technical-environmental planning processes in the later stages of the project lifecycle, rather than incorporating the closure perspective into routine social performance analysis from the outset. Social life is not a static reality. It is in a constant flux and does not follow a linear path unlike engineering processes. Therefore, this perspective, adding the social “issues” to existing technical and environmental planning processes, weakens the capacity and possibilities to respond to social reactions related to the closure process (Finucane, 2008; Vanclay et al., 2015).

Mine closures do not simply mean the end of production. From a social perspective, it is a process in which different social dynamics evolve, and new forms manifest themselves in different structures. The literature repeatedly emphasizes that understanding mine closures not as a singular stage of a linear process, but as a holistic process, is the most accurate approach (Chaloping-March, 2008; Bainton & Holcombe, 2018). Mines can go through stages of maintenance and repair, temporary closure, transfer of ownership, partial closure, decommissioning, or abandonment. The social perception and interpretation of these professional processes, dominated by miners, can be quite different from that of the local communities. For the local population, these institutional or regulatory distinctions are evaluated according to the material and social realities that they entail.

This reconceptualization of the concept of mine closure has significant consequences. It means that closure must be addressed from a historical, relational, and even political perspective, not just on a national but also on a local level. Historical decisions, local relationships, past grievances, the withdrawal of the state during the neoliberal process, and unbalanced development processes shape how closure is experienced and interpreted (Bainton & Holcombe, 2018; Demajorovic et al., 2022).

2.2. Social License to Operate, Legitimacy, and Operation Termination

The concept of SLO is central to current discussions on mining governance, but its application to the closure process is limited and partial. In most institutional and policy settings, SLO is associated with operational legitimacy. In other words, the focus is on whether a project has sufficient trust, acceptance, and local tolerance to continue its operations (Prno & Slocombe, 2012). However, communities do not recognize legitimacy based solely on operational performance. They also evaluate a mine based on the expected closure process.

Demajorovic et al. (2022) demonstrate that SLO, community participation, and vulnerability are increasingly emerging as key analytical issues in the mine closure literature. Yet, the concept is still not sufficiently developed in the context of mine end-of-life. Academic discussions point to the importance of addressing not only the concept of SLO but also what could be called a “social license for closure.” This is not merely a rhetorical extension of SLO and signals a significant shift in perspective. Closure is becoming a test of the perception that a mining project has been terminated responsibly, burdens have been fairly

redistributed, and a socially sustainable post-mining future has been ensured (Demajorovic et al., 2022; Everingham et al., 2020).

This perspective also reveals why the sectoral legacy remaining from the closure process is important for future projects. Communities do not evaluate new mines in a historical singularity. They interpret them in light of cumulative experiences. Incomplete remediation works, unresolved compensation issues, unemployment, abandoned infrastructure, destroyed landscapes, and distrust of institutions become elements of reputational memory (Bainton & Holcombe, 2018; Owen & Kemp, 2018). In this sense, the performance of closure becomes a socially accumulated archive of past corporate behaviors. This shapes expectations, skepticism, and risk perceptions regarding current and future investments.

The legitimacy dimension of the closure process cannot be limited solely to regulatory compliance. Formal approval of a closure plan does not automatically guarantee social legitimacy, or that the closure process will be perceived as fair, credible, or socially acceptable. The key concept here is effective participation, and meaningful monitoring at the local level, attention to social fault lines, and many other factors are vital to the legitimacy of the closure process (Everingham & Mackenzie, 2019; Everingham et al., 2020; Demajorovic et al., 2022). As Demajorovic et al. (2022) point out, effective participation requires not only the formal inclusion of communities in decisions regarding land use and the post-mining future, but also the strengthening of their capacity to participate technically and politically in these decisions.

2.3. Social Anthropology, the Mining Sector, and the Social Dimension of Closure

Social anthropology offers a unique conceptual framework for understanding why mining activities are socially significant. At its most basic level, anthropology opposes reducing the mining sector solely to the field of engineering. D'Angelo (2015) argues that mining cannot be adequately understood from a purely technical or engineering perspective. Such a perspective can lead to ignoring the complexity of the social relationships established around mines and their social, political, and economic impacts. Ballard and Banks (2003) similarly emphasize that mining should be analyzed not as a neutral area of development or production, but within the context of power relations, which are a field of deep conflict. In addition to this debate in the literature, Özkan's (2014, 2019) applied anthropology perspective emphasizes that development projects only become socially understandable when local cultural norms, forms of authority, and patterns of social organization are considered not as a byproduct of technical planning, but as a central element from an analytical perspective, and opens up a discussion on the power of the ethnographic method in this context.

As Özkan (2019) points out, ethnography is defined not only by a set of methods but also by a specific field relationship based on "being there," that is, physical presence, participant observation, and an interpretive interaction with daily life. "Being there" remains one of the defining hallmarks of ethnographic research.

As mentioned above, while closure is often treated as a matter of design criteria and technical implementation, an anthropological perspective and ethnographic method question what social life forms are constructed around mining activities, what kinds of dependencies and affiliations are formed, what claims to land and belonging emerge, and how the closure process redistributes value, authority, and uncertainty (Ballard & Banks, 2003; Golub, 2019; Welker, 2009). These questions redefine the closure process not merely as an engineering process, but as a process of social reorganization.

Mining anthropology also highlights the disputable nature of mining worlds. Ballard and Banks (2003) define mining as a field of "resource wars" where corporations, states, communities, and other actors clash with each other through unequal power relations. Naturally, there is no innocent or homogeneous side in these arenas. Encounters related to mining present a socially heterogeneous, politically fragmented, and historically layered reality. Closure reproduces this complexity. Different groups within the same settlement may have different interests and agendas regarding closure timing, layoff arrangements, land use, environmental standards, compensation, or many other issues (Golub, 2019; Herman, 2010).

External intervention in a society or community can cause the re-formation and transformation of many social formations. By its very nature, mining activities occur within the context of spatial fixation and, in this context, create a significant vector effect on the transformation of communities adjacent to the mining site. Golub (2019) shows that mining can change how people understand space, time, and themselves. Environmental transformation can disrupt not only land use but also the perception of local history, sense of belonging, and even moral systems. Studies on former mining towns show how mining areas are transformed into emotional spaces (Everingham & Mackenzie, 2019; Jiskani et al., 2026). Closed mine sites are often

spatial sources of evocative emotions such as grief, attachment, nostalgia, and resistance. These are not merely emotional byproducts; they shape how people perceive the closure and imagine the post-mining future.

From this perspective, mine closure is not simply a matter of transitioning from one economic situation to another. It is also a process in which communities renegotiate their identities, memories, and the moral meaning of the end of mining activity.

3. Ethnography and Mine Closure: Methodological Justification

3.1. Why Standard Participation Tools are Insufficient

Various tools are now commonplace in mine closure processes: public participation meetings, stakeholder meetings, grievance mechanisms, household surveys, consultation minutes, and socio-economic reporting. These tools are certainly not invaluable. However, at least in practice, whether created due to legal obligations, at the request of funding institutions, or as part of the internal practices of the mining companies themselves, these tools generally have a procedural format. Consequently, these tools are often more successful in recording already expressed concerns than in identifying or predicting the social dynamics that lead to the risk of closure (Vanclay et al., 2015; Vanclay & Esteves, 2024).

This is precisely where the importance of ethnography emerges.

Vanclay and Esteves (2024) define ethnography as an approach based on long-term involvement in the daily life of a group, careful observation, reflective dialogue, and contextual interpretation. They warn that without ethnographic work, impact assessment experts risk asking irrelevant questions in the local context and receiving superficial or generic answers. Ethnography enables practitioners to understand which questions are truly important in a given context, how affected groups interpret change, and what meanings are attributed to project impacts. This is particularly important in mining environments where formal stakeholder categories often mask internal social differentiation and inequality in exposure to risk (Ballard & Banks, 2003; Herman, 2010). In his work, Özkan focused on the practical strengths of applied anthropology, arguing that local social and cultural patterns, informal leadership, and historically established authority relations cannot be sufficiently extracted from desk assumptions or short-term consultations, but instead require ethnographic interaction with the people who will actually live with the results of the project (Özkan, 2014). As Özkan (2019) takes it further, ethnographic fieldwork does not end with simply arriving in the field. “Participant observation,” expressed as “being there,” is the dominant research technique of ethnography and also requires penetrating the field, generating new questions as information accumulates, and transforming observations into permanent written records that allow the researcher to revisit, organize, and reinterpret social processes over time.

Participant observation and “being there” are vital in closure processes. Risks associated with closure often don’t initially manifest as a formal complaint. They emerge in more diffuse and relational ways: A rumor about being laid off, a contractor’s concern about increasing debt, an elderly person’s distrust of rehabilitation promises, a woman’s increased burden of unpaid care after losing her job, a young worker’s intention to emigrate, a local dispute over who will be entitled to the land in the future, an unspoken fear that previous promises will once again not be fulfilled. Such developments may go unnoticed by formal advisory systems until they escalate into conflict or closure (Everingham et al., 2020; Owen & Kemp, 2018).

3.2. Ethnography as a Situational and Introspective Method

The most distinctive feature of ethnography is that it is designed to understand social life in a processual, contextual, and meaning-laden way. Ethnography progresses through tools such as long-term participant observation, in-depth interviews, field notes, contextual reading, and continuous and iterative interpretation (Vanclay & Esteves, 2024). Its power lies not in producing abstract, “representative” data detached from context, but in observing how relationships, categories, and experiences are formed in practice.

Vanclay and Esteves (2024) emphasize that ethnography can reveal local values, power relations, social differentiation, symbolic systems, and social spaces. Ethnography also has a reflective quality. Researchers should pay attention not only to the participants but also to their own positions, ethical understandings, access routes, and impacts in the field. This reflexive quality is important in environments where power asymmetries are often profound and external researchers can be assessed through the institutional ties they

carry (Ballard & Banks, 2003; Herman, 2010). Similarly, Özkan (2019) emphasizes that ethnographic competence encompasses more than just a method in a narrow procedural sense.

Ethnography offers at least five methodological advantages in terms of mine closure processes. First, it reveals diversity within seemingly uniform communities. Second, it uncovers the informal institutions, decision-makers, and hidden hierarchies that shape closure outcomes. Third, it traces how social meanings are attributed to work, land, compensation, and future prospects. Fourth, it identifies power disparities and unbalanced vulnerabilities within households and communities. Fifth, it can bring to light emerging risks before they are formalized (Vanclay et al., 2015; Vanclay & Esteves, 2024; Everingham & Mackenzie, 2019). In addition, the ethnographer's craft relies on practical skills, particularly in relation to closure contexts. This includes learning by discarding assumptions and judgments that may arise through prior knowledge, adapting to uncertain field conditions, and systematically recording the material for later interpretation and triangulation (Özkan, 2019).

3.3. Applied Anthropology, Institutional Ethnography, and Participation Ethics

The ethnographic application in closure planning should not be confused with a naive or romantic defense of localism. In this context, ethical discussions are one of the most important areas of debate in applied anthropology, and mining anthropology, and specifically the evaluation of anthropology and ethnography in the closure process, is not exempt from these discussions. As mentioned above, anthropological knowledge and ethnographic data have the potential to provide valuable inputs for the development of different institutional strategies. They can also provide highly valuable inputs for the mining context, where institutional actors have a higher capacity to order, disseminate, and functionalize information (Ballard & Banks, 2003; Welker, 2009). This is precisely why methodological reflexivity and ethical clarity are vital.

Herman's (2010) corporate ethnographic study on mining and "community support" discusses how categories such as support, consent, and local residency can be administratively managed to mask more complex relationships of conflict and compromise. Therefore, an ethnographic approach to mine closures should pay attention not only to community life but also to how corporations, consultants, and regulatory systems classify and solidify community reality.

The practical power of anthropology lies in its capacity to identify the social and cultural conditions that determine whether interventions will be successful or create unintended harm (Özkan, 2014). The anthropologist's advantage lies not only in access to the field, but also in their capacity to interpret local culture, values, and social organization in ways directly relevant to impact assessment and project design. Özkan (2019) further expands on this point by emphasizing that ethnography cannot be separated from accumulation of and craftsmanship: Ethnographic knowledge develops through repeated observation, transforming the field notes into analytical texts, and the disciplined refinement of questions in the field. In the mine closure process, this means moving beyond procedural consultation to a deeper engagement with how the closure is actually experienced and negotiated. When used correctly, applied ethnography not only improves communication but also enhances the essential quality, realism, and fairness of closure planning.

3.4. Result-Oriented Ethnographic Research Application

Ethnography, which focuses on "being there," is interpretive rather than statistical. However, because ethnography, with its interpretive nature, is evaluated with a result-oriented approach, a series of analytical processes are followed in interpreting and evaluating the obtained data.

The methodological structure proposed below points to a result-oriented ethnography. The logic of this structure is also nourished by previous field experiences obtained from ethnographic SIA studies conducted in Türkiye. In these studies, field studies lasting one to three months were conducted to identify forms of authority, land ownership, conflict memory, and social differentiation that are important at the local level and are ignored by technically focused project planning (Özkan, 2014). It is also nourished by Özkan's (2019) discussion, which considers ethnographic writing and field notes not only as tools for subsequent reporting but also as constitutive parts of the field study:

1. Contextual and historical review: Compilation of local histories related to mining, previous closure experiences, conflict processes, land ownership arrangements, and institutional trust relationships.

2. Participant observation: Continuous presence in mining-affected communities and, where possible, relevant institutional settings to observe how closure is discussed, anticipated, or becomes controversial in practice.

3. In-depth qualitative interviews: Semi-structured and open-ended interviews with workers, former workers, contractors, women, youth, seniors, landowners, local authorities, civil society representatives, and other local actors.

4. Mapping household livelihoods: Analysis of how income, services, liabilities, and informal economic flows linked to mining activities are integrated into household survival strategies.

5. Stakeholder and power mapping: Identification not only of stakeholders but also of internal divisions, informal authorities, advocates (gatekeepers), marginalized groups, and unequal capacities to influence closure decisions.

6. Narrative and discourse analysis: Paying attention to rumors, public narratives, expectations, memory, and disputed meanings regarding compensation, rehabilitation, and the post-mining future.

7. Iterative feedback and triangulation: Providing feedback to participants on provisional interpretations and triangulating between interviews, observations, documents, and planning records.

8. Layered field note practice: Maintaining draft notes, descriptive analytical notes, and reflective writings to preserve empirical details, support ongoing interpretation, and separate observed processes from the researcher's more personal reactions and judgments.

The methodological design proposed above aligns with the practical needs of closure planning in two ways. First, it can provide a deeper foundation of knowledge than standard socio-economic profiling. Second, it can transform ethnography into management-meaning outputs without reducing it to raw consultation data. From a practical standpoint, outputs of such studies could include differentiated social background information, locally based closure criteria, stakeholder scenario maps, vulnerability profiles, participant monitoring indicators, and early warning triggers for adaptive management (Vanclay et al., 2015; Everingham et al., 2020; ICM, 2019). As Özkan (2014) argues in the context of SIAs of HEPPs, while the cost of such research is often marginal compared to total project budgets, its capacity to prevent avoidable conflicts and misperceptions can make a significant difference.

For Türkiye in particular, such an approach would require sensitivity to regional differences, variations in mining intensity, rural livelihood structures, expectations regarding employment and compensation, local political mediation, and the collective memory of past mining and infrastructure projects. The aim is not to universalize a single ethnographic template, but to establish a methodological rationale for how ethnography can contribute to closure planning in socially intense and politically diverse contexts.

4. Closure-Focused Ethnographic Framework

Three operational entry points can be mentioned where ethnographic information can be integrated into mine closure planning. These are:

- Social closure reference point and social closure criteria,
- Stakeholder and land-use scenarios,
- Screen alert and adaptive management during demobilization.

These entry points are considered not as separate stages, but as overlapping areas where social information can shape the planning, implementation, and evaluation processes.

4.1. Social Closure Reference Point and Social Closure Criteria

The first starting point is the creation of a social reference framework specific to mining activities. Traditional reference studies usually only present aggregate socioeconomic indicators such as population, employment, access to services, education, and income. Undoubtedly, these indicators are of fundamental importance, but they are not sufficient. They rarely reflect how mining is actually integrated into daily life. These indicators do not adequately reveal how wage income circulates through kinship networks, how contracting economies support local households, how gender-based workforce redistributes when wages are cut, how entitlement expectations are formed, or how trust and mistrust shape interpretations of the closure process (Vanclay et al., 2015; Everingham et al., 2020).

The literature on mine closure acknowledges the need for initial case studies and SIAs to address these shortcomings. Bainton and Holcombe (2018) argue that initial case studies should help correct company-

centric social risk models that prioritize risks to the success of the closure process while giving less importance to the risks the closure poses to local communities. They also highlight the importance of tools such as community sensitivity analysis, participatory multi-criteria analysis, and stakeholder mapping. Ethnography deepens these tools by moving from descriptive profiling to contextual interpretation (Vanclay & Esteves, 2024).

A community closure frame of reference supported by ethnographic data will reveal dependencies on livelihoods, mobility patterns, social obligations linked to mining revenues, dependencies on services, local political intermediaries, informal exchange systems, and histories of reconciliation with grievances. It will also determine how different groups define a “good closure” and what kinds of outcomes they find fair, reliable, or feasible. This distinction is particularly important because closure rarely affects all groups in the same way or on the same timeline (Everingham & Mackenzie, 2019; Demajorovic et al., 2022). Previous ethnographic SIA experiences in Türkiye reinforce this point. Seemingly insignificant or invisible social structures, such as sub-tribal formations, land ownership histories formed according to topographical diversity, or local associations, can be decisive for the legitimacy of the project when ethnographically defined (Özkan, 2014).

Such studies directly contribute to the criteria of social closure. The ICMM Closure Maturity Framework identifies elements such as stakeholder engagement, post-closure land use, social and economic transition, success criteria, and monitoring (ICMM, 2019). However, these frameworks fall short of specifying how these criteria should be socially grounded. Ethnographic research can help determine not only which criteria should be included, but also who will define these criteria and how they will be validated at the local level.

4.2. Stakeholder and Land Use Scenarios

The second approach point of the ethnographic framework in the context of mine closure concerns stakeholder analysis and post-closure land use scenarios. In many closure processes, land use is treated as a matter of technical planning in an almost entirely formal process shaped by environmental feasibility and formal consultation processes. Anthropology reveals that this is insufficient. Land should not be considered simply a neutral surface to be reallocated after mining. It is intertwined with the people living on it, communities, culture, and, more importantly, current human relations, livelihoods, demographic data, and many other social aspects (Ballard & Banks, 2003; Golub, 2019).

While Golub (2019) shows that mining transforms people's perception of space and time, D'Angelo's (2015) discussion on mining and the environment points to the multifaceted values attributed to landscapes, waters, and lands. Closure planning that approaches the site solely from a biophysical suitability perspective risks overlooking the social and symbolic significance of post-mining land use. Such omissions have the potential to produce significant negative consequences.

Aware of these consequences, the practice of ethnographic scenario building aims to overcome these challenges by posing more difficult questions than traditional consultation processes. By recognizing, defining, and even attempting to understand the communities living on that site, it prepares input for the creation of different scenarios, thereby enabling a process consistent with a call for participatory and locally based future building in closure design (Everingham & Mackenzie, 2019; Everingham et al., 2020).

Research on former mining towns shows that infrastructure, degraded landscapes, abandoned facilities, and settlement patterns continue to function as mnemonic and emotional landscapes. Attachment to the place, nostalgia, grief, and solastalgia influence how communities address the post-mining future. These are not merely emotional responses; These are situational forms of knowledge that shape political action, resistance, and local legitimacy (Jiskani et al., 2026).

4.3. Early Warning and Adaptive Management During Demobilization

The third entry point is the closure phase, the period when the shutdown process becomes urgent in terms of material and social aspects. This phase is generally a period when employment contracts end, supply activities decrease, contractors leave, uncertainty increases, and tensions escalate. However, shutdown monitoring systems generally remain heavily reliant on environmental and regulatory compliance indicators, and their capacity to detect early-stage social tensions remains limited (ICMM, 2019; Everingham et al., 2020).

It should not be overlooked that social unrest is at a very high level during this process, especially since it marks a transition period, and therefore a period of uncertainty. Ethnography contributes to this by making it possible to detect weak signals within the community before they escalate into conflict or long-term harm. Such signals include migration planning, household debt, changes in local governance, increased reliance on informal economies, intra-family tensions, rumors about compensation or severance pay, social fragmentation, appropriation of closure compensation by certain segments of the community, and re-referencing past grievances. These are emerging dynamics that standardized monitoring systems often fail to capture in a timely manner (Owen & Kemp, 2018; Vanclay & Esteves, 2024).

Demajorovic et al. (2022) argue that closure planning requires meaningful indicators in the local context and that participatory monitoring is important in terms of both environmental and socioeconomic dimensions. Ethnography strengthens this thesis, primarily because it helps determine what should be considered a meaningful signal. Ethnography moves monitoring beyond administratively useful metrics to socially meaningful metrics.

In this context, adaptive governance is not merely an administrative slogan. This concept implies that closure teams are willing to revise sequencing, communication, support measures, land-use planning, or monitoring priorities in response to ethnographic findings. The practical value of ethnography is most clearly revealed here: It enables closure planning to respond to social reality as it develops, rather than after it has been formalized as grievance, conflict, or failure.

5. The Importance of an Ethnographic Approach in the Mining Environment in Türkiye

An ethnographic approach is particularly important in Türkiye because social relations in mining areas are rarely limited to formal stakeholder categories. Regional differences, rural livelihoods, kinship networks, labor migration, local political mediation, land-use traditions, and informal authority structures shape how mining projects are interpreted and discussed. Standard tools of participation can record formal opinions, but often overlook the social fabrics where the risk of closure actually occurs (Vanclay et al., 2015; Vanclay & Esteves, 2024).

In many regions of Türkiye, the social significance of mine closures may be linked not only to direct employment in the mines but also to intertwined livelihoods in areas such as dependence on subcontractors, seasonal and cyclical labor movements, local retail economies, transport links, expectations of reciprocity, and agriculture, livestock farming, or small trade. Ethnography is particularly well-suited to tracing these interdependencies. Furthermore, it can determine how the closure of the mine redistributes the burdens within households, particularly along gender and generational lines, and what future different groups envision after the cessation of mining activity (Everingham et al., 2020; Demajorovic et al., 2022).

The broader comparative lesson drawn from applied anthropology in Türkiye is also important in this context. Özkan's (2014) social studies within context of HEPPs highlight that development projects often fail when they disregard local social organization, informal leadership, historical land relations, and cultural patterns. Using examples from Siirt, Çorum, Giresun, and Kütahya, he demonstrates that ethnography can identify socially significant formations overlooked by routine consultation processes: Sub-tribal structures, historically rooted basin conflicts, opposition shaped by cumulative impacts of previous projects, and seemingly folkloric but politically influential organizations are examples of dynamics that can determine the fate of local investments.

Similar dynamics apply to mining operations in general, and to mine closure processes in particular. Even a technically competent closure process can lead to social conflict if it fails to understand how local support, opposition, silence, or fragmentation emerges.

In Türkiye, closures should be considered not as an afterthought, but as a fundamental determinant of trust. A technically sound but socially inadequate closure can deepen skepticism toward future projects while failing to meet formal obligations. In contrast, a closure process that incorporates foundational studies based on ethnographic information, differentiated stakeholder analysis, socially based land-use scenarios, and adaptive monitoring is more likely to support a trustworthy transition. This is not merely a normative argument; it is also a practical one. Ethnography can improve the quality of decisions by enhancing understanding of local context-specific risks, expectations, and vulnerabilities, and reduce the likelihood of foreseeable social harms translating into reputational, political, or financial liabilities (Owen & Kemp, 2018; Everingham & Mackenzie, 2019; Jiskani et al., 2026).

In this sense, ethnography should be seen not as an optional descriptive supplement, but as an integral part of closure management.

6. Conclusion

The issue of mine closure is still very often addressed from a purely technical and environmental perspective. However, the literature reviewed here clearly demonstrates that closure is equally a social and political process. This process redistributes livelihoods, reshapes the future of the region, reveals institutional weaknesses, and leaves memories that determine the legitimacy of future mining activities (Bainton & Holcombe, 2018; Demajorovic et al., 2022; Jiskani et al., 2026). Therefore, the insufficient consideration of the social dimensions of closure is not a minor deficiency. This is a structural weakness in current approaches to mine closure.

This article argues that anthropology and ethnography offer a particularly strong response to this weakness.

Anthropology helps to reconceptualize the concept of “closure” as a contested process embedded in power relations, cultural meanings, spatial ties, and historical memory (Ballard & Banks, 2003; D’Angelo, 2015; Golub, 2019).

Ethnography provides methodological tools to investigate these dynamics not only as they are administratively represented, but also as they are experienced (Vanclay & Esteves, 2024).

This allows closure planning to grasp pluralism within communities, identify hidden vulnerabilities, understand how legitimacy is socially produced, and detect emerging risks before they escalate into formal crises.

The article proposes a closure-focused ethnographic framework structured around three main headings: the basic condition and criteria of social closure, stakeholders and land-use scenarios, and early warning and adaptive management in the demobilization process. It also presents a methodological framework that will enable this approach to be implemented in practice.

For Türkiye, where mining governance is increasingly shaped by social acceptance, such an approach is particularly timely. The legacy of closures already influences how mining projects are conceived and evaluated. Ignoring this fact weakens both planning and legitimacy. Therefore, the article's central argument is quite clear. If mine closure is one of the moments when mining activities are most intensely assessed by the affected communities, then closure planning must be capable of grasping not only the physical consequences but also the social worlds that the closure disrupts, reshapes, and leaves behind. Ethnography is indispensable for this task because it makes visible the lived realities where closures become either socially credible or socially damaging.

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Reindustrialising the Oil Shale Mining Region: Designing Industry Symbiosis Readiness Industrial Parks

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Abstract

The North-East Estonian oil shale region is entering a transition phase in which competitiveness increasingly depends on the ability to retool industrial land, infrastructure, and capabilities into new value chains. This study examines the role of technology/industrial park development as concrete mechanisms for economic redevelopment and industrial symbiosis, focusing on opportunities in industrial areas of Ida-Viru County.

The research asks how industrial parks with ready-made infrastructure and available plots can be structured as “symbiosis-ready” platforms that accelerate investment decisions and enable cross-firm exchanges of energy, materials, water, by-products, and services. The empirical basis is an opportunity mapping and governance analysis built around an industrial park portfolio and its stated regional focus on manufacturing-oriented investment attraction, including parks in Narva, Kohtla-Järve, Jõhvi, and Kiviõli.

The analysis integrates stakeholder consultations to identify (i) infrastructure and capacity conditions that matter for symbiosis (grid and substation capacity, potential direct connections to power generation, and the availability of serviced land), (ii) anchor-industry and supplier opportunities (e.g., chemical and cleantech-adjacent value chains), and (iii) governance/financing instruments that reduce transaction costs for co-location and shared-utility investments, including incubator-type facilities.

The outputs are already in practice in the oil shale transition region: a set of park-level design principles for enabling industrial symbiosis (tenant-mix logic, shared infrastructure, data and coordination mechanisms), and regional development instruments can be aligned with industrial park development to deliver job-creating, investment-ready post-mining redevelopment.

Keywords: Reindustrialising, Oil Shale, Industry Symbiosis

1. Introduction

The North-East Estonian oil shale region is entering a transition phase in which competitiveness increasingly depends on the ability to retool industrial land, infrastructure, and capabilities into new value chains. In post-mining settings, redevelopment is rarely a purely technical land-reuse exercise. It is also a delivery challenge: whether a region can convert legacy assets into credible, investable opportunities that reduce uncertainty for firms and accelerate decision-making under constraints related to time, capital intensity, and multi-actor coordination. As industrial systems are reconfigured, the central question becomes how to organise redevelopment to support both investment attraction and the long-term performance of the emerging industrial ecosystem.

Technology and industrial parks provide a concrete mechanism to operationalise this transition by packaging land, utilities, and administrative conditions into an “investment product.” However, parks designed mainly for plot occupancy risk leave significant value on the table if they do not enable cross-firm integration that lowers costs and increases resource productivity. This study, therefore, treats industrial parks not only as sites for co-location but as platforms that can be structured to enable industrial symbiosis. Purposeful exchanges of energy, materials, water, by-products, and services, when the enabling conditions are designed and governed explicitly. In the following Figure 5 shows the North-East Estonian oil shale industry region.

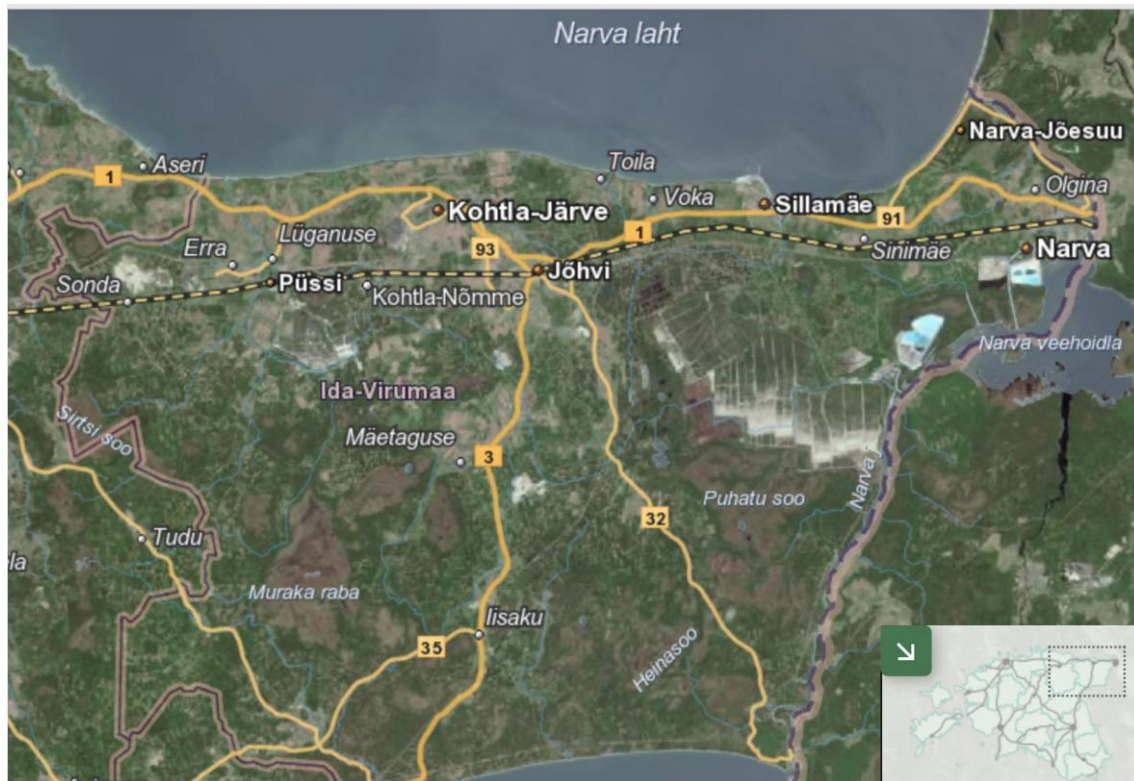


Figure 1 Ida-Viru County

1.1. Post-mining transition and the regional competitiveness challenge

For transition regions, competitiveness is increasingly shaped by speed and credibility: how quickly sites can move from “available land” to implementable, investment-ready projects, and how reliably utilities and permitting interfaces support industrial operations. In the oil shale context, legacy infrastructure and industrial capabilities may offer advantages, but these advantages are not automatic. They become economically meaningful only when they can be translated into clear conditions for connection, scaling, and coordinated development that match investor requirements.

A practical implication is that redevelopment strategies must address both asset configuration and transaction costs. Even where physical assets exist, investments can stall if responsibilities, timelines, and risks are fragmented across multiple actors. In this setting, the performance of redevelopment mechanisms should be judged not only by plans and announcements, but by their ability to reduce early uncertainty and to create repeatable pathways from interest to commitment and implementation.

1.2. Technology and industrial parks as a concrete redevelopment mechanism

Technology and industrial parks are widely used to support redevelopment because they can bundle serviced land and access to infrastructure into a structured entry point for firms. For manufacturing-oriented investment attraction, this bundling can shorten lead times by reducing the number of separate negotiations required for land readiness, utilities, and administrative interfaces. In a transition region, that reduction in early-stage complexity is particularly valuable because infrastructure conditions are often uneven and the costs of misaligned assumptions are high.

At the same time, a conventional park model often focuses on land uptake rather than on system outcomes. From a transition perspective, it matters whether co-location contributes to industrial renewal through shared utilities, integrated services, and exchange opportunities. Not only whether plots are filled. This motivates a shift in how parks are designed and governed: from passive real-estate offerings to active platforms that can coordinate multi-firm development and enable deeper industrial integration.

1.3. Industrial symbiosis and the meaning of “symbiosis-ready”

Industrial symbiosis describes mutually beneficial cross-firm exchanges of energy, materials, water, by-products, and services, typically enabled by proximity and coordination. In principle, industrial parks are natural environments for symbiosis because they concentrate firms and infrastructure. In practice, however, proximity is insufficient: the implementation of symbiosis depends on whether the necessary conditions, capacity, interconnection feasibility, information flows, and coordination mechanisms are in place when decisions are made.

This study uses the term “symbiosis-ready” to describe industrial parks that are intentionally structured to make symbiosis feasible and investable. Symbiosis-readiness is treated as a design target expressed through three linked elements: (i) infrastructure and capacity conditions relevant to exchanges (including grid and substation capacity, potential direct connections to power generation, and availability of serviced land), (ii) an anchor–supplier opportunity logic that increases the probability of viable exchange relationships (including chemical and cleantech-adjacent value chains), and (iii) governance and financing instruments that reduce transaction costs for co-location and shared-utility investments, including incubator-type facilities.

1.4. Research question, empirical basis, and contribution

Study asks: How can industrial parks with ready-made infrastructure and available plots be structured as “symbiosis-ready” platforms that accelerate investment decisions and enable cross-firm exchanges of energy, materials, water, by-products, and services? The empirical basis is an opportunity mapping and governance analysis of an industrial park portfolio in Ida-Viru County, including parks in Narva, Kohtla-Järve, Jõhvi, and Kiviõli, complemented by stakeholder consultations focused on symbiosis-relevant constraints and enabling conditions.

The contribution is applied and implementation oriented. Rather than proposing an abstract ideal for industrial symbiosis, the study synthesises portfolio-level insights into practical park-level design principles and enabling instruments to support investment-ready post-mining redevelopment. The aim is to provide a structured way to connect infrastructure readiness, industrial opportunity pathways, and governance/finance instruments into an actionable platform logic for transition-region industrial parks.

2. Materials and Methods

Ida-Viru Investment Agency (IVIA) is the regional investment promotion agency for Ida-Viru County in northeast Estonia, where the Estonian Oil Shale industry is also located. As a public agency, IVIA promotes the region to foreign investors to diversify the local economy and business environment and create new jobs, an institutional mandate that directly aligns with the post-mining redevelopment challenge addressed in this study.

IVIA’s core activity is the development of industrial parks across Ida-Viru County, with a stated delivery pipeline of 300+ hectares of serviced industrial land in Kohtla-Järve; Kiviõli; Jõhvi, as shown in Figure 2 and in Narva, as shown in Figure 3. In addition to industrial park development, IVIA implements other strategic development projects, including a Digital & Multimedia Incubator with a film stage, the Narva–Olgina Business Park with an aerodrome, and residential development initiatives in Jõhvi and Kohtla-Järve. Activities that together position IVIA as a central platform actor in the region’s economic transition. (IVIA 2026)

Given this remit, the empirical focus of the study is structured around the same industrial park portfolio that IVIA develops and promotes. IVIA’s public-sector foundation model, established by the Government of the Republic of Estonia together with the city/municipal governments of Narva, Jõhvi, Kohtla-Järve, and Kiviõli, also serves as a relevant institutional reference point for the governance analysis and stakeholder-facing elements of the research design presented in the following subsections.



Figure 2 Jõhvi Business Park (photo by Ida-Viru Investment Agency)



Figure 3 Technology park in Narva (photo by Ida-Viru Investment Agency)

2.1. Study design and scope

The study uses an applied, design-oriented approach focused on industrial park development as a mechanism for post-mining economic redevelopment. The unit of analysis is the industrial park as a platform, understood as a bundle of land and infrastructure readiness, an investment attraction proposition, and a governance arrangement capable of coordinating shared utilities and multi-firm development. The scope is limited to industrial areas in Ida-Viru County with stated ambitions related to manufacturing-oriented investment attraction and redevelopment in the transition context.

This approach is suitable because the question at hand is not only whether symbiosis is conceptually desirable, but how it can be operationalised through park development choices. The paper therefore focuses on identifying enabling conditions and instruments that reduce uncertainty and transaction costs, rather than modelling a single industrial exchange in detail.

2.2. Portfolio focus and case context

The empirical basis is built around an industrial park portfolio that reflects the region's redevelopment ambitions. The portfolio includes parks in Narva, Kohtla-Järve, Jõhvi, and Kiviõli. This portfolio framing supports a structured analysis of what “symbiosis-readiness” implies for parks that may differ in their infrastructure conditions, development maturity, and investment positioning, while still operating under the same regional transition context.

The portfolio perspective also aligns with the underlying redevelopment reality: investors and public actors typically evaluate not a single site in isolation, but a set of options, and regional transition outcomes depend on how these sites collectively support a pipeline of investable projects. For this reason, the paper treats parks as components of a broader redevelopment system and asks what conditions must be present at the park level for the system to generate symbiosis-enabled investments.

2.3. Evidence base: opportunity mapping, governance analysis, and stakeholder consultations

The analysis integrates three evidence components. First, opportunity mapping is used to capture how parks position themselves for manufacturing-oriented investment attraction, including their emphasis on ready-made infrastructure, available plots, and sector opportunity narratives. Second, a governance analysis examines how parks can reduce transaction costs associated with co-location and shared-utility investments, including which instruments are needed to coordinate multiple actors and reduce implementation friction. Third, stakeholder consultations are integrated to surface the practical constraints and enabling conditions that are often decisive in real investment decisions.

Stakeholder consultations are used specifically to identify infrastructure and capacity conditions that matter for symbiosis and investment acceleration. These include grid and substation capacity, the feasibility of direct connections to power generation, and the availability of serviced land. The consultations also help specify anchor-industry and supplier opportunity pathways, particularly those aligned with chemical and cleantech-adjacent value chains, and they inform which governance and financing instruments are most relevant for reducing transaction costs in the regional context.

2.4. Analytical lens: operationalising “symbiosis-readiness”

To operationalise the concept of a symbiosis-ready park, the analysis focuses on three interconnected dimensions derived from the research question. The first dimension is infrastructure and capacity readiness, with particular attention to electricity capacity constraints and the availability of serviced land. The second dimension is industrial opportunity logic, focusing on anchor industries and supplier ecosystems that can plausibly support cross-firm exchanges. The third dimension is enabling governance and finance, focusing on the instruments and organisational arrangements that reduce transaction costs for shared infrastructure and coordinated development, including incubator-type facilities.

This lens supports a synthesis that is directly actionable for park development and regional transition planning. Rather than treating industrial symbiosis as an abstract aspiration, the analysis identifies concrete design and instrument choices that can be embedded into park development plans and aligned with regional development instruments.

3. Results and Discussion

3.1. Symbiosis-relevant capacity conditions shape investment readiness

A central result of the analysis is that symbiosis-readiness begins with a small set of binding-capacity conditions that shape both feasibility and the speed of investor decision-making. Grid and substation capacity are particularly decisive because they affect whether energy-intensive manufacturing and process activities can be hosted, whether connection timelines are predictable, and whether parks can credibly market their readiness beyond generic “available land” claims. In a transition region where investor confidence depends on delivery certainty, capacity conditions function as a primary filter for which redevelopment opportunities can move from concept to investment.

The feasibility of direct connections to power generation is another capacity condition that matters for symbiosis, as it can shape how energy flows and how energy-related services could be configured across tenants. Where direct connections are feasible, they can support more integrated approaches to energy supply, shared infrastructure, and potentially more competitive operating conditions. The availability of serviced land is equally critical because it determines how quickly tenants can establish operations and whether parks can plan interconnections and utility corridors to avoid costly retrofitting later.

Together, these conditions indicate that parks become symbiosis-ready not through branding alone but through credible, investable infrastructure readiness. Symbiosis-readiness, therefore, requires that parks develop and communicate capacity conditions in a way that aligns with investment decision needs and with multi-firm development pathways.

3.2. Anchor–supplier opportunity pathways increase the probability of viable exchanges

The opportunity mapping highlights the importance of anchor-industry and supplier opportunities as the second pillar of symbiosis-readiness. Industrial symbiosis is more likely when parks are designed around an ecosystem logic in which anchors and suppliers can co-develop, rather than around a purely opportunistic tenant mix. In this portfolio, chemical and cleantech-adjacent value chains represent a plausible opportunity space because they can connect to existing industrial capabilities while offering pathways for new manufacturing-oriented investment.

The anchor–supplier logic matters because it links investment attraction to the feasibility of exchange. Anchors can provide stable demand for utilities and services and can justify shared infrastructure investments that would be too risky or too costly for a single tenant. Suppliers and adjacent firms can form complementary demand profiles, creating opportunities for by-product exchange, shared services, and coordinated logistics. In a transition region, this ecosystem logic also supports workforce and capability upgrading by creating clearer clusters of competence development around identifiable value chain directions.

This result implies that parks should treat tenant selection and investment attraction as a design problem. A symbiosis-ready park does not merely accept any tenant that fills a plot; it builds a coherent development thesis around anchors, suppliers, and the exchanges and shared infrastructures that can make co-location economically and operationally compelling.

NPM Narva (Neo Performance Materials, Canada) serves as a clear anchor tenant for Narva's industrial park offering, converting the park from a "ready land + utilities" proposition into a proven high-tech manufacturing location. In Figure 4 the factory equipment is shown on the opening day in 2025.

The new 100 million EUR magnet factory in Narva Industrial Park, producing magnets for electric vehicles, wind generators, medical devices and other applications. The plant began with test-batch production, employing ~100 people from 14 countries, with expectations to grow to ~400 jobs in the coming years; expansion could increase output from 2,000 t/year to up to 5,000 t/year, with a longer-term potential of up to 1000 employees. The investment also signals strategic relevance for European industrial policy, as previously ~90% of such magnets were produced in China, and the Narva plant is framed as reducing Europe's dependence on that supply. The factory received €14.7 million from the Just Transition Fund, and both park leadership and company management explicitly link further growth to infrastructure conditions, particularly energy availability, renewable supply, and price, as well as the importance of public–private partnerships to accelerate additional production opportunities. (Kundla, 2025)



Figure 4 Opening of the new NPM Narva magnet factory (photo by Sergei Stepanov/ERR)

3.3. Governance and financing instruments are required to reduce transaction costs

A third result is that transaction costs, coordination burdens, risk allocation, and financing frictions are major determinants of whether symbiosis-enabled co-location becomes a reality. Even when exchange opportunities exist in principle, they may not be implemented if no actor has a clear mandate to coordinate shared investments and if no practical instruments exist to structure and finance shared utilities. For this reason, governance and financing instruments are not “add-ons” but core components of symbiosis-readiness.

The analysis identifies the need for instruments that reduce transaction costs for co-location and shared-utility investments. Such instruments include governance arrangements that clarify who can convene partners, how decisions are made, and how responsibilities are allocated across public and private actors. Financing instruments are needed to make shared infrastructure investable, particularly when it serves multiple tenants and requires coordinated CAPEX decisions. Incubator-type facilities are relevant in this context because they can reduce entry barriers for smaller firms and help create a pipeline of tenants aligned with the park’s anchor strategy, thereby strengthening the demand base for shared services and utilities.

This result shifts the practical question from “What symbiosis opportunities exist?” to “What instruments make those opportunities implementable?” In transition-region redevelopment, the instrument layer often determines whether the region can move from planning to delivery.

The “incubator-type” facility in Ida-Viru County is IDA Hub (<https://idahub.ee/en/>). IDA Hub Film and Multimedia Innovation Centre was founded by IVEK, IVIA and Tehnopol.

IDA Hub complements industrial-park redevelopment by building an innovation and SME pipeline around digital and creative-economy solutions. Within IDA Hub, the Tehnopol Startup Incubator’s Film and Multimedia Accelerator supports teams developing multimedia, VR/AR (virtual reality / augmented reality), storytelling platforms and other digital solutions for the film and creative sector, combining a structured 7-part training programme (business model, product/service development, legal, finance, sales/marketing, pitching) with an individually assigned lead mentor, up to 30 hours of mentoring and access to a wider mentor network. In Figure 5 the IDA Hub facility shows opportunities to develop cultural products from Ida-Viru County.



Figure 5 Industrial landscape of Ida-Viru County give also cultural opportunities (photo by IDA HUB)

3.4. Park-level design principles for “symbiosis-ready” industrial parks

Synthesising the above results, the study proposes a set of park-level design principles that operationalise symbiosis-readiness. Each principle is written as an implementation-oriented proposition that can be embedded into park development and aligned with regional development instruments.

The first principle is to treat tenant-mix logic as a system design choice. Parks should explicitly pursue an anchor–supplier ecosystem approach that increases the probability of viable cross-firm exchanges. This requires that investment attraction narratives specify not only sectors but also the operational complementarities that make co-location valuable, including potential energy, material, water, by-product, and service exchanges.

The second principle is to prioritise infrastructure and capacity transparency as an investment acceleration tool. Parks should develop a clear and investor-relevant articulation of grid and substation capacity conditions, connection pathways, and the availability of serviced land. Because these conditions shape feasibility and timelines, transparency reduces uncertainty and enables more credible engagement with manufacturing-oriented investors.

The third principle is to structure shared infrastructure as a deliberate development pathway rather than an afterthought. Symbiosis often requires shared utilities and interconnections, which are most cost-effective when planned early. Parks should therefore incorporate shared infrastructure planning into their development logic, including how multiple tenants could be served through coordinated upgrades and shared corridors.

The fourth principle is to establish data and coordination mechanisms that make exchange opportunities discoverable and implementable. Symbiosis-readiness requires more than proximity; it requires a mechanism for identifying exchange opportunities, clarifying feasibility conditions, and coordinating implementation steps among multiple actors. Parks should therefore institutionalise a coordination role and a process for translating opportunities into concrete, staged projects.

The fifth principle is to deploy governance and financing instruments that reduce transaction costs for co-location and shared-utility investments. Without such instruments, multi-firm projects can stall at the negotiation-and-risk-allocation stage. Parks and regional development actors should therefore use practical vehicles and instruments to enable shared investments and accelerate implementation.

The sixth principle is to integrate incubator-type facilities into the symbiosis-ready platform. Incubators and shared facilities can reduce entry barriers, increase the diversity and density of potential suppliers and service firms, and support a tenant pipeline aligned with anchor strategies. In turn, this strengthens the demand base for shared utilities and coordination mechanisms, helping parks evolve into functioning industrial ecosystems rather than static real-estate offerings.

3.5. Aligning regional development instruments with industrial park development

A final discussion point is that symbiosis-readiness cannot be achieved solely through park-level decisions if regional development instruments are not aligned with park development needs. The analysis indicates that regional instruments can be aligned with industrial park development to deliver job-creating, investment-ready post-mining redevelopment. Alignment is especially important for infrastructure upgrading, coordinated investment attraction around anchor–supplier ecosystems, and the governance and financing instruments needed for shared utilities.

This alignment perspective reinforces the study’s platform logic. Industrial parks become effective transition mechanisms when integrated into a regional redevelopment system in which infrastructure, governance, investment attraction, and capability development reinforce one another rather than operating as fragmented initiatives. In the context of the oil shale transition, this integrated approach is positioned as a practical way to convert legacy assets into a forward-looking industrial base.

4. Conclusion

This study examined how technology and industrial park development can serve as concrete mechanisms for economic redevelopment and industrial symbiosis in the North-East Estonian oil shale transition region. The study asked how parks with ready-made infrastructure and available plots can be structured as symbiosis-ready platforms that accelerate investment decisions and enable cross-firm exchanges of energy, materials, water, by-products, and services. Using an opportunity mapping and governance analysis of an industrial park portfolio in Ida-Viru County, covering Narva, Kohtla-Järve, Jõhvi, and Kiviõli, and integrating stakeholder consultations, the study identified three core elements of symbiosis-readiness.

First, symbiosis-readiness depends on infrastructure and capacity conditions that shape feasibility and time-to-investment, particularly grid and substation capacity, potential direct connections to power generation, and availability of serviced land. Second, it depends on an anchor–supplier opportunity logic that increases the probability of viable exchanges, including chemical and cleantech-adjacent value chains. Third, it depends on governance and financing instruments that reduce transaction costs for co-location and shared-utility investments, including incubator-type facilities that strengthen tenant pipelines.

The main output is a set of park-level design principles that operationalise symbiosis-readiness through tenant-mix logic, shared infrastructure planning, and data and coordination mechanisms, while emphasising the need to align regional development instruments with industrial park development. These principles are intended to support job-creating, investment-ready post-mining redevelopment by making industrial parks not only places where firms locate, but platforms where integrated industrial systems can be built.

Acknowledgments

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Employment of Former Miners in the German Drilling Industry

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Abstract

Over the past five decades, German drilling companies have hired former miners on at least three occasions after the closure of major mining activities, which represents post-mining developments with positive effects on labour transformation. Miners from the coal, uranium and ferrous as well as non-ferrous metal sectors are highly skilled and well-educated workers. As a result, the drilling companies evolved from conventional well-drilling companies into specialised companies offering services such as geotechnical investigations, geothermal purposes, and special foundation engineering. Today, the future of the German drilling industry appears very promising due to the requirements of the energy transition, infrastructure backlogs, and assessment of geological risks related to climate change. In this study, the author, who was closely involved in two of these transformation phases, provides insight into Germany's dual education system and other vocational training instruments

Keywords; Labour transformation, Dual education system, Drilling companies

1. Introduction

Structural changes in the German mining sector during the second half of the 20th century and the beginning of the 21st century resulted in several waves of labour transition from mining into related industrial sectors. Among the industries that benefited from this transition, the drilling sector occupies a particularly important role. Drilling companies were able to integrate former miners due to their technical competence, practical experience, geological background, and established safety culture.

Several historical developments that contributed the availability of qualified mining personnel for the drilling industry are:

- **Coal crisis in 1958:** This marked the beginning of a long-term decline for German hard coal mining.
- **Closure of Germany's two remaining hard coal mines in 2018:** The gradual closure of hard coal mines had taken place in the Ruhr area since the beginning of the coal crisis and the two remaining mines, Prosper-Haniel in Bottrop and Ibbenbüren, were shut-down at the end of 2018.
- **End of uranium mining in Eastern Germany:** Following reunification in 1990, SDAG Wismut was transformed into Wismut GmbH, owned by the Federal Republic of Germany.

These developments released large numbers of highly skilled workers into the labour market. Many of them possessed competencies in drilling technology, geological interpretation, machinery operation, and safety management, making them suitable candidates for employment in the drilling industry. Consequently, German drilling companies were able to expand their activities from traditional water well drilling towards specialised services, including geotechnical investigation drilling, geothermal drilling, environmental drilling, and drilling related to special foundation engineering. Former miners contributed significantly to this technological and organisational development.

2. Personal Experience in Vocational Training and Professional Development

My role as an instructor has involved in vocational training and professional development within the drilling industry since 1998. Personal involvement in the education and qualification of drilling personnel has provided first-hand insight into the transformation processes affecting the workforce.

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Since 2001, I have served as an instructor within the German dual vocational training system, contributing to the education of apprentices in drilling-related professions and additionally participated in examination committees for apprenticeship training, responsible for assessing vocational qualifications and ensuring compliance with nationally defined training standards.

During the most recent geothermal boom, I chaired an examination committee as second deputy chairman, coordinating examinations and ensuring the quality and consistency of certification procedures. Furthermore, I have organised and delivered training and continuing education courses for professionals within the drilling sector.

3. The Dual Vocational Education and Training System in Germany

A distinctive feature of workforce qualification in Germany is the dual vocational education and training system (Duales Ausbildungssystem). This model effectively combines practical training within a company with theoretical instruction at a vocational school as shown in Figure 1.

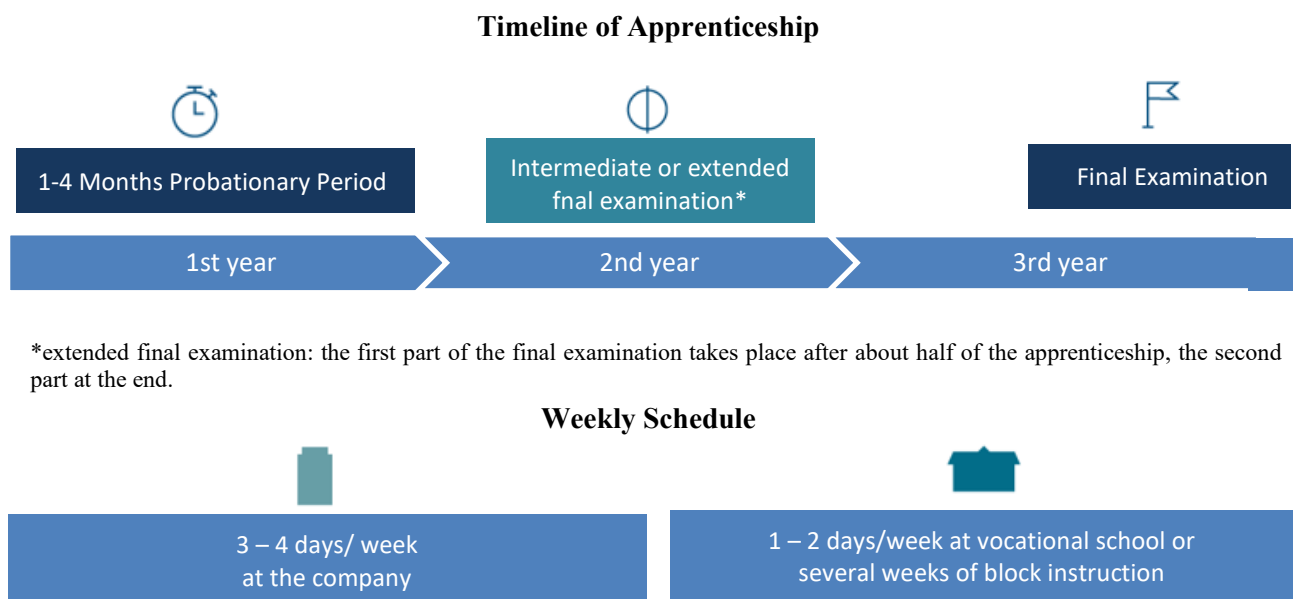


Figure 1: Dual vocational system schemata (BMBF, 2026a)

Typically, apprentices spend three to three and a half years acquiring professional competencies through a structured training programme. Companies provide practical training, while vocational schools deliver theoretical knowledge related to technical subjects, safety regulations, and industry standards. Upon successful completion, apprentices receive a formally recognised qualification issued by the relevant Chamber of Commerce and Industry as well as Chamber of Crafts.

In contrast to the dual vocational training system, training for certain professional fields takes place entirely at technical schools or vocational colleges (Fachschulen or Berufsfachschulen). Therefore, these forms of training are also referred to as full-time school-based vocational training. Additionally, there are special formats such as the integrated dual study program, a combination of dual vocational training and a Bachelor’s degree, or specific training programs for high school graduates (Abiturientenprogramme) in the retail sector. These formats are specifically aimed at students with a university entrance qualification (Abitur). These differences are given in Figure 2.

Historically, the dual system has ensured a high level of technical competence within German industries, including drilling and geotechnical engineering. Many former miners transitioning into drilling companies were able to complement their practical experience with formal qualifications through this system.

Despite the proven effectiveness of the dual education system, Germany currently faces a shortage of applicants for vocational training positions, particularly in technically demanding sectors such as drilling, construction, and geotechnical services as shown in Figure 3. This shortage poses a significant challenge for maintaining the future workforce of the drilling industry.



Figure 2: Dual vocational systems in Germany (BMBF, 2026)

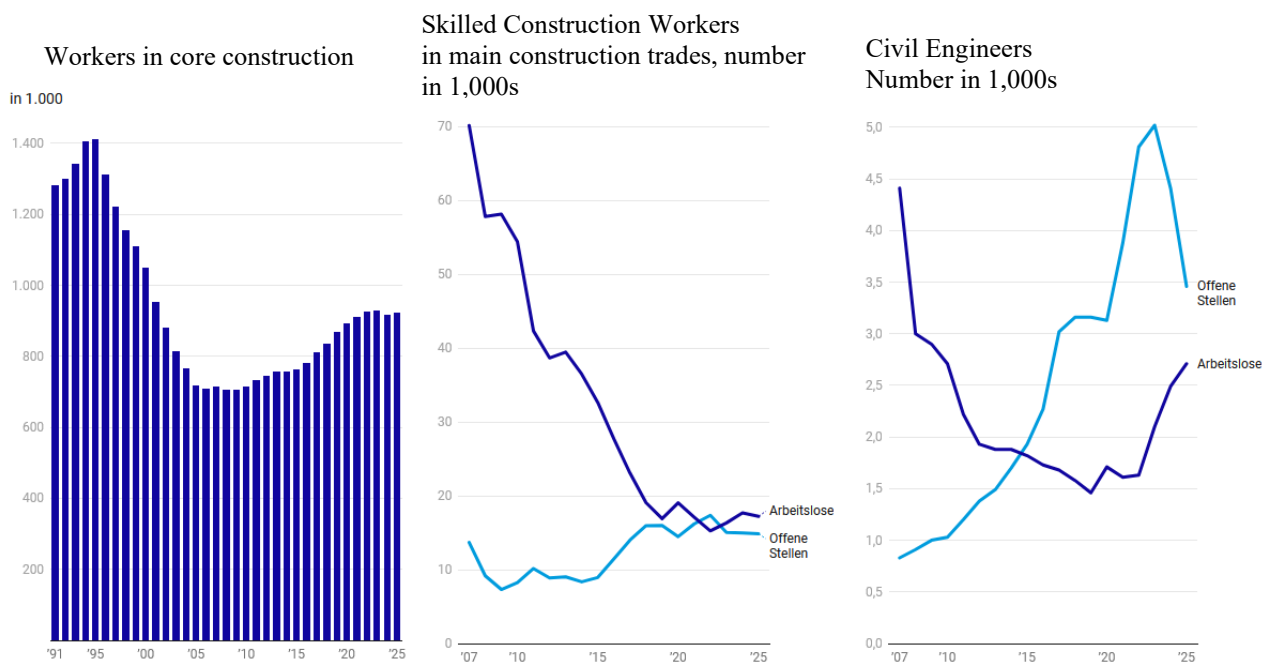


Figure 3: Employment and unemployment in the main construction trade (Bauindustrie, 2026)

4. Vocational Continuing Education and Industry Associations

Beyond initial vocational training, continuing professional education plays an essential role in maintaining the high level of competence required for drilling personnel. In Germany, such training including specialised courses, seminars, and certification programmes is often organised through associations of the construction industry and craft sector associations.

These initiatives address technological developments, new regulatory requirements, and emerging fields such as geothermal energy, environmental monitoring, and advanced geotechnical investigations.

Despite the existence of multiple training providers and programmes, there is considerable value in maintaining a unified and standardised training framework. A consistent curriculum helps ensure that personnel across the industry possess comparable levels of knowledge and competence. Equally important is the development of a standardised catalogue of examination questions. Such a catalogue should be designed with appropriate pedagogical considerations and tailored to the specific target groups participating in the training programmes, including apprentices, skilled workers, technicians, and engineers.

5. Examination Committees in Vocational Education

A key component of vocational qualification in Germany is the examination committee system. These committees are responsible for conducting final examinations and ensuring that professional standards are maintained across the sector. To ensure a fair and comprehensive assessment, examination committees are typically composed of representatives from three main groups:

- **Employers**, representing industry interests and operational requirements
- **Vocational teachers and trainers**, providing practical and theoretical expertise from the educational system
- **Academic or scientific representatives**, providing scientific and normative expertise

This tripartite structure ensures a balanced evaluation process that integrates practical experience, educational methodology, and scientific knowledge. As a result, vocational qualifications maintain both industry relevance and educational integrity.

6. Conclusion

The transition of former miners into the German drilling industry represents an important example of successful labour transformation in response to structural economic change. These workers with mining backgrounds have contributed significantly to the development of modern drilling services in fields such as geotechnical investigation, geothermal energy, and special foundation engineering.

The German dual vocational education system, together with structured continuing education programmes and the oversight of examination committees, has played a crucial role in facilitating this transition. However, the current shortage of applicants for vocational training highlights the need for renewed efforts to attract and retain young professionals in these technically demanding industries.

As the demand for drilling services grows, driven by the energy transition, infrastructure development, and climate-related geological risk assessment, ensuring a well-qualified workforce will remain a key priority for the future of the German drilling industry. Maintaining the standards of the German drilling industry will depend on our ability to adapt our training frameworks to meet these future challenges.

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Appropriate Communication and Engagement for Mining Projects from Cradle to Grave

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Abstract

Although the mining industry plays a fundamental role in modern society and the global energy transition, mining frequently faces significant challenges in public perception. Current communication strategies adopted by the mining industry globally often fail to effectively convey the necessity and benefits of mining, resulting in mistrust, opposition, and a compromised social license to operate. This paper identifies systemic failures in existing communication approaches, analyses the underlying causes, and proposes a comprehensive "cradle-to-grave" communication framework. The framework emphasises the importance of evolving communication from sharing dry technical data with local communities and society as a whole to engaging empathetically/tolerantly, transparently, and proactively, using appropriate language and diverse channels throughout a project's lifecycle. The advantages offered by mining companies in terms of Corporate Social Responsibility (CSR) and its impacts on the local and wider community need to be improved and developed. By adopting these strategies and project-specific innovative methods, the mining industry can enhance societal perception, collaboratively secure its social licence, and ensure that its vital contributions are recognised and welcomed in daily life.

Keywords: Communication, mining, society, language, environment, project-lifecycle

1. Introduction

The mining sector is an essential “pillar” of modern civilisation, providing the raw materials that support virtually every consumptive aspect of our daily life, from infrastructure to advanced technologies. Although mining professionals understand society’s needs and take pride in providing the essential raw materials that society demands, the public's understanding and acceptance of mining projects are heavily influenced by negative media coverage. Society's understanding of the essential role of the mining industry lags, creating a significant gap in the industry's social license to operate. This paper identifies systemic failures in existing communication approaches, analyses the underlying causes, and proposes a comprehensive "cradle-to-grave" communication framework by highlighting its conceptual nature after some literature review.

The communication between professionals makes sense, but when the same message is pitched to ordinary people, it fails to convey the intended message, “the important role mining plays to satisfy society's demand for structure and technology,” to the intended social target groups.

As an example, a survey conducted across 32 countries by “Globe Scan” for “ICMM” in 2023 demonstrated the industry’s image in public perception (Globe Scan & ICMM, 2023) (Figure 1). Respondents were asked to consider mining in general, rather than focusing on specific activities in their country. The survey results indicated that the public has poor perceptions of the mining industry, which remains a persistent challenge for the sector in fulfilling its responsibilities to society, and the mining industry still trails all other sectors tested (including oil and gas) in many countries.

While perceptions of the mining industry are largely negative, particularly due to environmental and social concerns, it is essential to understand that people have not entirely written off the mining sector, provided it can demonstrate improved performance and a more socially acceptable “face”. The public does

not understand the mining industry's prioritisation of environmental management and the stringent compliance with the IFC Performance Standards and the Equator Principles, which international lenders and investors demand. This is a face of mining that is never presented as it would fall on “deaf ears”, meaning the people do not want to hear it! It is more fashionable to criticise and join the bandwagon of “anti-mining” strategies practised by the media and celebrities, which are often ill-informed and not objective.

The survey results also showed that nearly four in ten (40%) people across the industrialised world believe mining companies are below average when it comes to fulfilling their responsibilities to society (Figure 2a, Figure 3). Except for Chile, the mining industry is generally seen as among the lowest performers of all 18 sectors tested when it comes to fulfilling societal responsibilities (Figure 2b).

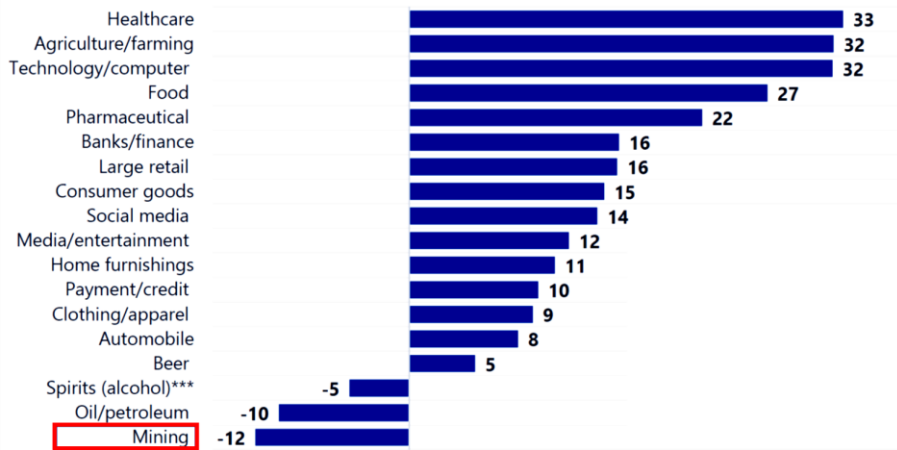


Figure 1. Public perception about the performance of industries in fulfilling their responsibilities¹⁾

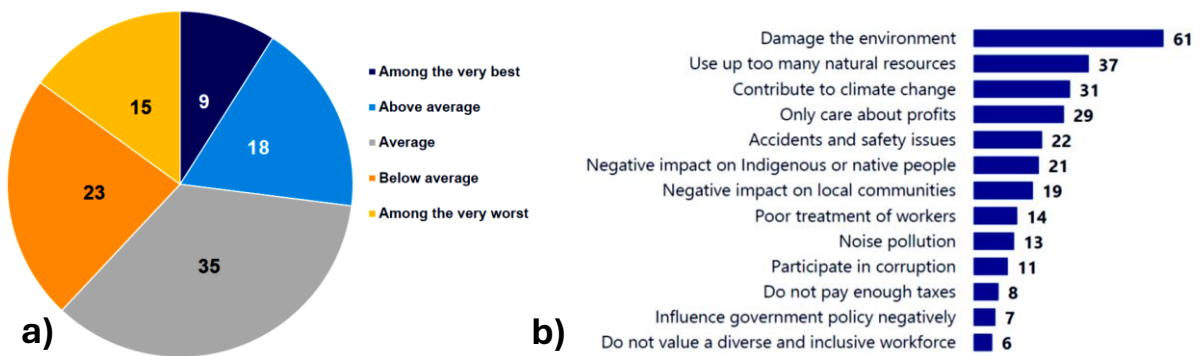


Figure 2. a)Public perception about the mining industry; b)Reasons why mining companies are below average in fulfilling their responsibilities^[1]



Figure 3. Perception in the sampled countries^[1]

Something that is not made clear is that the perception of mining is proportional to the contribution that mining makes to the GDP or the economies of countries, and how many are actively, directly and indirectly employed in mining. Countries like Australia and South Africa have a more informed impression of mining; they still have levels of opposition, but the opposition is informed and understands the nuances of mining. It is to these nuances that this paper is appealing to “inform” and communicate the important part mining plays globally in sustaining public demand. Essentially, public demand is the demand for all products which are manufactured or produced including all metals and minerals, they are mined because there is a demand – the message is “don’t shutdown the supply, shutdown the demand” – stop buying jewellery, cars, mobile phones, cameras, etc; subliminal message “don’t treat the symptom, treat the cause”.

However, another report conducted by CSIRO (Moffat et al., 2024) in 2024 based on a national survey on Australian attitudes toward mining shows important shifts in public perception, with trust in the mining industry in Australia improving from 2.8 in 2014 to 3.1 in 2024 (on a 1-5 scale), suggesting a more informed public on “what mining does and is” and acceptance is also increasing on the access to critical minerals being essential for achieving net zero emissions and mining being important element for the Australian way of life and Australia’s future prosperity. However, despite strong support for mining, the majority still perceives that mining has negative environmental impacts. Whilst the economic contribution of mining and its importance in supporting the energy transition are widely recognised, building trust, ensuring fair distribution of benefits, and actively engaging communities are key to maintaining the industry’s social license (52% of participants agree that mining communities receive a fair share of benefits).

It is important to understand the demographics of public perception, where public opinion is often made with minimal or tainted knowledge by those who do not have any direct or indirect reliance on mining and have never lived near a mine or in a mining community. Whereas, within a mining community, the opinion or question is not asked. This is not a balanced societal review or commentary, so there is minimal communication between these sections of society.

Public trust in the mining industry in Australia is strongly linked to procedural fairness, with community engagement and governance playing central roles in maintaining the industry’s social licence to operate. This points to the growing importance of local mining communities working with the industry and holding them accountable, reflecting a shift in public expectations around transparency and local involvement. Another strong predictor of social acceptance is the extent to which the perceived benefits of mining (e.g. economic value) outweigh its negative impacts (e.g. environmental impacts). As Australia’s mining sector expands to meet the global demand for critical minerals, maintaining trust, actively engaging with communities, ensuring equitable local and wider societal benefits, addressing local environmental concerns, and highlighting mining’s role in the energy transition will be critical to its long-term success. The part played by central and state governments is important to understand, politically mining is essential to GDP and jobs, both critical elements for any government so the influence of mining is considerable in certain states (Western Australia and Queensland) but less so in New South Wales, Victoria, Tasmania and Northern Territory where mining has left legacies which from old mining initiative over 100 years old in most cases. So, as with any industry, the youth, maturity, and old age have completely different situations and understandings in the public perception. Youth = financial investment; maturity = sustained financial benefits; and old age = clean-up!

Although Australia has had limited success in effectively conveying its positive message to society, the data from the Globe Scan study highlights the urgent need for the industry to adopt and develop effective communication tools.

2. The Strategic Priority: Effective Public Communication

Mining is the fundamental source of raw materials essential for nearly everything we consume, enabling technological advances that shape modern civilisation. The public often overlooks the commonality of mined materials, despite their undeniable presence in daily life and the fact that the public demand is what drives exploration and mining.

Mining operates as the cornerstone of the supply chain for raw materials, providing essential resources that are the basis of numerous fields and technologies. From the extraction of culturally and economically important precious metals such as gold and silver, which are pivotal in electronics and jewellery manufacturing, to the mining of industrial minerals like iron, coal, limestone, nickel, cobalt, aluminium

(bauxite) and copper, which are critical for construction and electrical engineering, the breadth of mined materials is vast and varied (Figure 4).

It is, therefore, no wonder that the list in Figure 4 contains very crucial materials in all aspects of societal development, in particular those associated with the huge demand for batteries. It is also no surprise that three fundamental commodities, coal, iron and cement making clinker, occupy the top of the list as they are three critical ingredients in power supply and steel making and in construction, on which the industrial and societal development is heavily dependent.

These resources in this list enable the development of innovations ranging from renewable energy technologies, such as solar panels that rely on extracted silicon, and aeolians (wind mills), to the production of batteries laden with lithium for electric vehicles and appliances (mobile phones).

Despite the integral role that these mined materials play across multiple sectors, their universality and commonality often lead to a lack of public awareness regarding the specific processes involved in that they are mined and the complexities surrounding sustainable mining practices. Acknowledging the importance of these materials is crucial for fostering an informed dialogue about responsible sourcing and the long-term impacts of mining on both the environment and society.



Figure 4. Global commodity production from mines in 2023 (from BGS, 2025)

Therefore, the language that the mining community uses becomes an essential ingredient in communicating with the public. During this communication process, a structured framework is essential as a useful tool to highlight the importance of mining.

This framework may include the following:

- Pitching mining's indispensable role in modern life back to society,
- Highlighting economic and societal contributions beyond extraction,
- Identifying current communication failures in message delivery as early as possible,
- Establishing a cradle-to-grave communication framework for every project, and
- Establishing phase-specific communication strategies.

2.1. Pitching Mining's Indispensable Role and the Energy Transition: Examples from Daily Life

Mining plays a crucial role in supporting modern life, without receiving full recognition for its contributions. Mining is the only way to provide the essential materials used in a wide range of products and

technologies, from infrastructure, such as roads and buildings, to everyday consumer goods that drive modern life forward. This sector provides essential materials that not only fulfil everyday needs but also advance the global energy transition toward sustainable practices. Throughout our daily lives, the widespread use of technology also underscores the extensive influence of mining. The buildings we live in and work in, the cars we use, the infrastructure we take for granted, and the smartphones and laptops that communicate and maximise our efficiency are just a small part of reality.

The development of technologies will always be based on terrestrial minerals (metals) until the time that Artificial Intelligence (AI) can “manufacture” minerals from digital terrains! The cycle/circle is clear but not conveyed to the public, and the public does not really care when they are in a buying frenzy for modern technologies. It is the education of the public that communication is aimed at.

Beyond its practical benefits, mining makes a significant contribution to economic growth by job creation, stimulating and contributing to local economies (medical, infrastructure, schools, etc) and supports infrastructure development, ultimately enhancing the quality of life in local communities, thus impacting directly and indirectly (workers and families as well as miners and suppliers/contractors).

From transportation systems reliant on mined metals and batteries to the electric grid that powers our homes and businesses, the mining sector's contributions are evident across virtually every aspect of life. Additionally, as the world transitions toward sustainable energy solutions, mining plays a crucial role in sourcing the materials needed for renewable technologies, such as solar panels and wind turbines, as well as the multi-metals used in batteries and cell phones. This development not only addresses environmental concerns but also drives further economic opportunities. Acknowledging the indispensable nature of mining fosters a more comprehensive understanding of its impact and value, especially in the context of current societal challenges and sustainability efforts.

In summary, mining is a vital component of wealth creation and societal technological and financial advancement. By providing the resources that fuel our civilisation, it enables progress and enhances our ability to face future challenges. Highlighting this reality with examples from our daily lives will reinforce the message about mining’s critical role in ensuring comfortable living conditions for society.

Although there are countless examples available to demonstrate the crucial role of minerals, the following highlights just a snippet from some of the everyday items:

Smartphones are highly complex devices, embodying a remarkable concentration of diverse elements. More than 50% of all components in a smartphone are derived from mineral commodities (Pitt, 2020). Approximately 70 out of the 83 stable elements on the periodic table can be found in a smartphone, including up to 62 different types of metals. The average weight of a cellular phone is estimated at around 100 grams.

Laptops similarly share many fundamental material characteristics with smartphones, being dense concentrations of various elements. A typical laptop can contain over 240 different substances (Meskers, et al., 2009) such as Al (54%), Cu (11%), Fe (11%), Mg (6%), Sn (4%), Ni (3%), Co (2%), Li (1%) and other elements (Si, P, As, Ga, B, Au, Ag, Ru, Zn, Ni, Pt, Ta, rare earth elements and many others).

1 H 1.00794																	2 He 4.002602
3 Li 6.941	4 Be 9.012182											13 B 10.811	14 C 12.0107	15 N 14.0067	16 O 15.9994	17 F 18.9984032	18 Ne 20.1797
11 Na 22.989770	12 Mg 24.3050											13 Al 26.981538	14 Si 28.0855	15 P 30.973761	16 S 32.065	17 Cl 35.453	18 Ar 39.948
19 K 39.0983	20 Ca 40.078	21 Sc 44.95591	22 Ti 47.867	23 V 50.9415	24 Cr 51.9961	25 Mn 54.938049	26 Fe 55.845	27 Co 58.9332	28 Ni 58.6934	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.64	33 As 74.92160	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.4678	38 Sr 87.62	39 Y 88.90585	40 Zr 91.224	41 Nb 92.90638	42 Mo 95.94	43 Tc [97.9072]	44 Ru 101.07	45 Rh 102.9055	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.411	49 In 114.818	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90447	54 Xe 131.293
55 Cs 132.90545	56 Ba 137.327	57 La* 138.9055	58 Ce 140.116	59 Pr 140.90765	60 Nd 144.24	61 Pm [144.9127]	62 Sm 150.36	63 Eu 151.964	64 Gd 157.25	65 Tb 158.92534	66 Dy 162.50	67 Ho 164.93032	68 Er 167.259	69 Tm 168.93421	70 Yb 173.04	71 Lu 174.967	
87 Fr [223.0197]	88 Ra [226.0254]	89 Ac** [227.0277]	90 Th [232.0381]	91 Pa [231.03588]	92 U [238.02891]	93 Np [237.0482]	94 Pu [244.0642]	95 Am [243.0614]	96 Cm [247.0704]	97 Bk [247.0703]	98 Cf [251.0796]	99 Es [252.0830]	100 Fm [257.0951]	101 Md [258.0984]	102 No [259.1010]	103 Lr [262.1097]	

Figure 4. Elements used in smartphones and laptops (modified Meskers et al 2009, and from MCC, 1996)

Household electrical devices represent a broad category of products, each with unique designs but sharing common material dependencies. Steel is a pervasive material in large electrical appliances. The outer casing and major structural parts of a washing machine and refrigerators are typically made of steel, often coated with zinc for corrosion protection (AMP, 2025). Steel accounts for a significant portion, ranging from 22 to 36 kg in a standard washing machine, making up 50-60% of its total weight, containing mainly Fe, Al, Cu, Si (Sigüenza et al., 2021; Claudia and Chirara, 2024) and approximately 60% steel in fridges. Stainless steel (an alloy of iron, chromium, and often nickel) is common in commercial refrigeration for its durability and corrosion resistance. Cu is present in the electric motors and electrical cables of washing machines. A refrigerator contains approximately 3% copper by weight [6]. Al is found in smaller quantities in electric motors and other lightweight components of washing machines. Refrigerators contain about 3% Al by weight.

Buildings, ranging from residential homes to large commercial complexes, utilise a diverse palette of materials, primarily derived from minerals, to achieve structural integrity, functionality, and aesthetic appeal. As the most widely used material globally, concrete is a composite made from fine and coarse aggregates mixed with a binder (cement) and water. It typically comprises 60-75% aggregates, 10-15% cementitious material, and 15-20% water by volume. Cement itself is primarily produced from limestone (~80%) and clay (~20%). Steel is extensively used for structural sections (reinforcing bars), roofing products (purlins and cladding), internal fixtures (rails and stairs), and utilities (pipes). It provides high strength and durability. One of the longest-lasting building materials, stone (e.g., sandstone, granite, marble), is used in walls and flooring, while bricks are structural clay blocks. Glass is used for windows and flat glass. Aluminium is used in various building components. Materials such as mineral wool insulation (29.3 MJ/kg) and fibreglass batt insulation are used for improving thermal performance. A typical composition for the materials used in the buildings is shown in Figure 5 (Lei, et al., 2023).

Significantly, the global push toward electrification and renewable energy has heightened the importance of mining, making it critical for achieving climate goals and ensuring energy security. For example, 73% of Australians, a nation reconciled with the mining activity, recognise that achieving net-zero emissions requires increased mining activity.

Solar panels, wind turbines, and electric vehicles (cornerstones of a low-carbon future) rely heavily on a consistent supply of minerals such as silicon, germanium, silver, copper, lithium, aluminium, nickel, cobalt, and zinc. The World Economic Forum estimates that approximately 3 billion tons of metals will be necessary to reach net-zero emissions by 2050 (World Economic Forum, 2020). This reliance underscores that without foundational materials, technological innovation is stalled, and the transition to a sustainable future becomes unattainable. The public's high awareness of the importance of these critical minerals, coupled with 66% of respondents supporting streamlined regulations to expedite the renewable energy transition, presents a significant opportunity for the industry to align its narrative with broader societal goals.

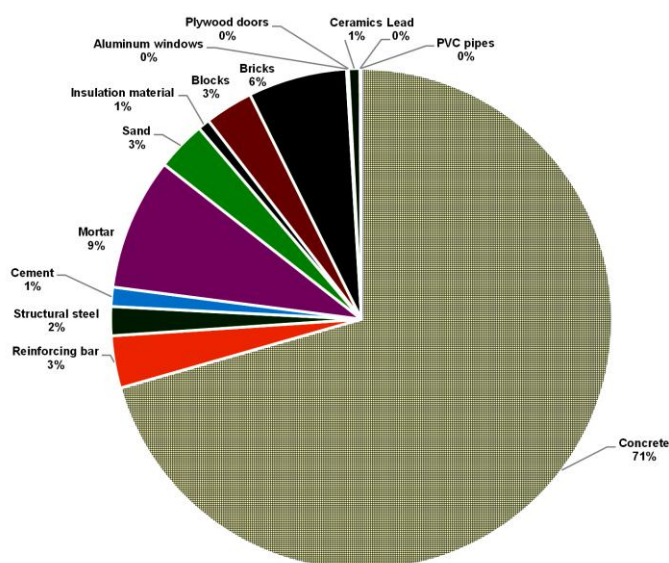


Figure 5 Average composition of material used in buildings (residential, office, commercial, and school) (modified from Lei [9])

Conventional motor cars are complex assemblies of hundreds of components, relying on a vast array of materials containing predominantly metallic parts, typically accounting for 75-80% of their total mass. Steel remains the most commonly used metal, comprising about 60-70% of an average car's weight (USGS, 2005). The distribution of elements in a typical car varies depending on the vehicle type, fuel type, and other characteristics. For a car with a mass larger than 1500 kg and an unknown engine size from the 2020 data, the estimated total mass of selected elements is as follows (Løvik et. al. 2021), : **Fe** (Largest component, primarily in steel and cast iron), **Al** (significant, especially in body, closures, and battery casings for electric vehicles), **Cu** (found in wiring, electronics, and electric drive motors), **Ag** (present in electronics and power electronics), **Au** (found in printed circuit boards), **Pt, Pd, and Rhodium (Rh)** (used in catalytic converters for internal combustion engine vehicles), **Neodymium (Nd) and Dysprosium (Dy)** (found in permanent magnets in electric drive motors), **Mg** (used in engine components, with lower amounts in electric vehicles), **Lanthanum (La)** (present in catalytic converters), **Si** (found in electronics and semiconductors and glass). Electric vehicles (EVs) generally contain more aluminium, copper, neodymium, and dysprosium due to their batteries, electric drive motors, and power electronics. Internal combustion engine vehicles (ICEVs) have higher amounts of iron and platinum group metals due to their engines and catalytic converters.

Roads are also fundamental to transportation networks, and their construction relies on a combination of natural and engineered materials. Aggregates form the bulk of road construction. They include crushed rock (limestone, igneous rock, sandstone) as the “hard core used in the road base” and natural sand and gravel, which are heavily compacted before the application of the surface layers. Aggregates constitute the majority of an ordinary densely graded asphalt mixture, typically 80-85% by volume. For the construction of 1 km. 1,600 tons of asphalt mix, 170 tons of black gravel (covered with bitumen), as well as 2,400 m³ of white or ordinary gravel and 2,500 m³ of sand are consumed in Category II roads with asphalt concrete pavement ^[13]. The main use of crushed rock is as roadstone in road construction, accounting for 41% of total crushed rock sold. Sand and gravel are primarily used for concrete (67% of total sand and gravel sold). Bitumen (Asphalt Cement), a highly viscous binder, holds the aggregates together (Wikipedia, 2025a). Cement itself is mined/quarried from limestone and crushed to a fine powder to mix with sand and aggregate to form concrete.

Asphalt concrete pavement mixes are typically composed of 5-10% bitumen and 90-95% aggregates. A high proportion of mineral powder (between 8-10%) is also used to create asphalt concrete layers with a high modulus of elasticity. Recycled Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) are increasingly incorporated into new asphalt mixtures. In 2019, new asphalt pavement mixtures in the United States contained, on average, 21.1% RAP and 0.2% RAS (Wikipedia, 2025b). Steel slag (SS) is also being explored as a partial replacement for conventional aggregates, with proportions varying from 2% for medium traffic roads to 4-8% for heavy traffic roads, showing benefits in stiffness and rutting resistance. The sheer volume of aggregates used in road construction, typically comprising 90-95% of asphalt concrete, highlights their fundamental role. These materials, including crushed rock, sand, and gravel, are essential for providing the structural backbone and load-bearing capacity of roads.

Ships are fundamental instruments to support the global economy by connecting the goods from where manufactured/produced to the rest of the world (<https://www.marinetraffic.com/en/ais/home/centerx:20.7/centery:-9.6/zoom:2>). They are large, durable vessels designed to withstand harsh marine environments, and their construction relies heavily on specific materials chosen for strength, corrosion resistance, and weldability. Steel (and correspondingly Fe) is overwhelmingly the most widely used material in shipbuilding, comprising about 86% of materials, whilst the other essential components include non-ferrous material, minerals, and copper present in machinery and cables, underscoring its foundational importance in maritime construction ^[16]. This extensive use necessitates materials with high strength, weldability, and toughness, coupled with robust resistance to marine corrosion.

The selection of specialised alloys, such as cupro-nickel (CuNiFer) for seawater systems and high-grade stainless steel (Inox) for corrosive environments, highlights the critical need for materials that can endure the harsh conditions of the ocean (Janin et al., 2016). This material choice directly impacts the vessel's lifespan, maintenance requirements, and overall operational safety. The reliance on specific mineral imports, such as nickel from Canada, which supplies roughly half of the United States' total nickel needs, illustrates the geopolitical dimension of maritime construction (Baskaran, 2025). Nickel alloys are critical inputs for defence and automotive industries, as is Antimony, which is used in armour plating for vehicles, ships, and personnel equipment, as well as jet engines and missile casings (Baskaran, 2025). This situation emphasises

the importance of securing diversified and stable supply chains for critical minerals to maintain national security and industrial capacity.

Bridges are critical infrastructure components designed for long-term structural integrity and resilience, relying on materials with high strength and durability. Steel is a primary material for bridges (structurally and in wire ropes), valued for its high strength, durability, and relatively light weight, which allows for lighter foundations and lower erection costs. Concrete is also extensively used in bridge construction, forming foundations, piers, and decks. A typical concrete mix consists of 60-75% aggregate, 10-15% cementitious material, and 15-20% water by volume (Caltrans, 2013). Cement itself is primarily composed of limestone (~80-90%) and clay (~8-20%), with other components like silica, alumina, and iron oxides. Aggregates for concrete include sand and crushed rock. The combined use of steel and concrete forms the foundational material system for modern bridges. Bridges are designed for very long service lives, often exceeding 75 to 100 years.

2.2. Economic and Societal Contributions Beyond Extraction

The impact of mining extends well beyond the extraction site, significantly contributing to socio-economic development and the well-being of host communities and nations. These broader contributions are often underestimated or poorly communicated, leading to a narrow public perception that views mining as solely focused on extraction at the expense of nature and the environment.

In countries dependent on natural resources for their economy, responsible mining practices can significantly reduce poverty and enhance social well-being, wealth creation, and quality of life.

The 2020 Mining Contribution Index (2020) provides scores and rankings that indicate the relative importance of mining to the economies of various countries (Figure 6). It shows that many of the world's most mining-dependent countries continue to rely heavily on their natural resources as the primary driver of economic activity. However, this index does not measure success. A country's relatively high position on the index does not necessarily translate into broader economic and social benefits, as this outcome depends on several other factors, with the quality of governance being a critical one.

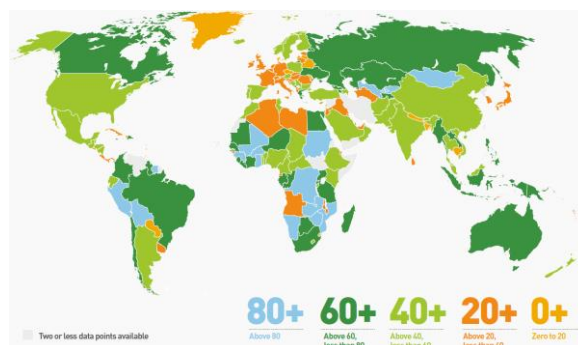


Figure 6 Mining Contribution Index for the various countries' economies [19]

In contrast, when countries are ranked solely on the monetary value of metals and minerals production, the top-ranking countries are dominated by upper-middle or higher-income economies (Figure 7). Only 6 other countries – India, Indonesia, Philippines, Ukraine, Zambia (lower-middle income) and the Democratic Republic of the Congo (low income) – feature in the top 20 countries based on production value.

The top 20 rankings have not changed significantly over the past two years, with Finland and Türkiye dropping out of the list, replaced by Zambia and the Philippines. This highlights the reliance of low- and middle-income countries on the mining sector. Among the top 25 ranked countries, 21 are also included in NRG's Resource Governance Index. Of these 21 countries, 84 per cent were rated as weak, poor, or failing by NRG. This suggests that there is room for improvement in practices that could enhance the economic benefits of mining, such as taxes and royalties, to support the achievement of the Sustainable Development Goals.

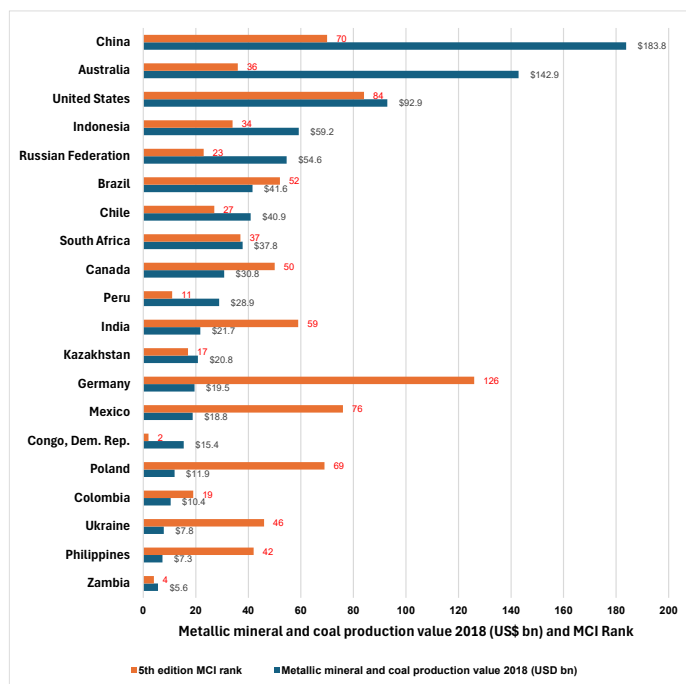


Figure 7. Top 20 countries ranked on the production value of metallic minerals and coal, and their MCI ranking (produced from ICM data [19])

To support the above argument, for example, the resources sector in Australia generated A\$271 billion in export revenue in 2020, which was more than A\$3 for every A\$5 raised, according to a Minerals Council of Australia analysis of ABS figures (Bravus Mining, 2021). Mining accounted for more than 10 per cent of the entire economy, the gross domestic product, making it the biggest sector of the national economy. Through tax revenues, including A\$15.2bn in state royalties alone, high wages and significant purchases of high-value plant and materials, mining-related money is one of the positive impacts of mining that flows through to people in our cities, small communities in regional areas, with services to assist everyone across the country.

Responsible mining practices in low- and middle-income countries that depend on mining can be transformative, leading to significant reductions in poverty levels and overall improvements in social well-being^[19]. However, effective mineral resource governance is essential to ensure that mineral wealth translates into broad-based economic and social progress. Thus, it is evident that more efforts are needed to maximise mining's contribution to national economies. The MCI indicates that many low- and middle-income economies continue to rely heavily on the metals and minerals sector both socially and financially.

In the meantime, the global integration that mining enables comes with vulnerabilities. Volatility in commodity prices threatens stability in export-dependent producer countries and can have extensive global economic consequences. For example, critical mineral prices have experienced substantial spikes and increased volatility in recent years, with lithium, cobalt, and nickel prices soaring by 738%, 156%, and 94%, respectively, between January 2021 and March 2022 (Bravus Mining, 2021). These fluctuations raise concerns about their impact on the ongoing energy transition, highlighted by the 2021 reversal of long-term cost reduction trends, with wind turbine and solar panel prices increasing by 9% and 16%, respectively (Tae 2022).

The influence of certain countries that have a monopoly on metals must not be underestimated. The rise and fall of metals prices is critical to mining company economics, but the time lag between metals price fluctuation and the impact on profitability is more or less immediate due to the nature of the price levels agreed between buyer and seller. The costs of the seller do not fluctuate in line with the sales price, as profitability is directly impacted.

Ericsson & Löf (2017) demonstrated in their study that there are 14 low-income countries, 33 middle-income countries and 3 high-income countries among the 50 countries with the highest Mining Contribution Index (MCI-W_r) score in 2016. This study showed that mining plays an important role, particularly in many low- and middle-income countries. Among the top 20 countries, Congo (DRC) has the highest score,

followed by Burkina Faso, Mali, Papua New Guinea and Eritrea. Chile and Australia show that, also in some high-income countries, mining remains a vital part of the national economy. African economies dominate among the top 20 countries, with 12 countries. The African mining vision of metals and minerals as important parts of African economic and social development is clearly well-founded. The results of this survey contradicted the widespread view that mineral resources create a dependency that might not be conducive to economic and social development. One conclusion of this survey is that mining countries perform better than oil-producing countries and non-mineral countries in Africa as measured by these indices of human development and governance. The mining sector's contribution to global trade is also significant, particularly for resource-rich developing countries. Many of these nations depend heavily on mineral exports, accounting for 10-20% of their GDP and 50% of total exports (Ericsson & Löf, 2017).

The same message was accentuated in a World Economic Report in 2020 (2020), which analysed 163 industry sectors and their supply chains and found that over half of the world's GDP is moderately or highly dependent on nature and its services. Construction (US\$4 trillion), agriculture (US\$2.5 trillion) and food and beverages (US\$1.4 trillion) are the three largest industries that depend most on nature. Combined, their value is roughly twice the size of the German economy. Such industries rely on either the direct extraction of resources from forests and oceans or the provision of ecosystem services such as healthy soils, clean water, pollination and a stable climate. Industries highly dependent on nature generate 15% of global GDP (US\$13 trillion), while moderately dependent industries generate 37% (US\$31 trillion).

This report also found that many industries have significant "hidden dependencies" on nature in their supply chain and may be more at risk of disruption than expected. For instance, there are six industries which have less than 15% of their direct gross value added (GVA) that is highly dependent on nature, yet over 50% of their supply chains' GVA is highly or moderately nature-dependent. These are chemicals and materials; aviation, travel and tourism; real estate; mining and metals; supply chain and transport; and retail, consumer goods and lifestyle.

Therefore, the mining industry is diversifying its commodity portfolio too. The share of coal producers among the top 40 mining companies has decreased from nearly half in 2012 to just a quarter by 2022 (Owais 2024). This change is driven by climate change concerns and a rising demand for minerals essential for clean energy applications, such as lithium, cobalt, and rare earth elements.

Electrification is becoming a key trend in mining, with OEMs developing hybrid and fully electric mining machinery. This transition reduces maintenance, emissions, and noise levels and therefore reduces costs, but increases power consumption. In return, the mining sector is increasingly adopting renewable energy solutions to minimise its carbon footprint. Hybrid and standalone renewable energy systems are being deployed to replace fossil fuels. Automation and robotics, such as autonomous trucks and drilling systems, are becoming the norm by enhancing productivity and safety while cutting fuel usage and maintenance costs; hence, legislation is needed to regulate.

For example, Australia is widely recognised as a global leader in the deployment and regulation of autonomous mining trucks, particularly in the Pilbara region of Western Australia. The state has developed a "Code of practice" for "Safe mobile autonomous mining in Western Australia," which provides a legal and regulatory framework for the use of autonomous vehicles in mines. This has allowed for the large-scale deployment of autonomous haulage systems, with Australia having the largest population of autonomous mining trucks in the world. While other countries like Germany have passed national laws on autonomous driving for public roads, Australia's efforts have been specifically and comprehensively focused on the unique environment of mine operations. Companies like Rio Tinto have been operating fully autonomous iron ore transport in Australia since 2016.

Whilst technological development needs to be encouraged, the abilities of lower-income nations to be able to support these developments are in question, as is the ability of the junior mining companies to afford the increased costs of more advanced machinery with less "choice" in the level of technology.

Collaborative efforts among major mining companies, governments, and local communities can foster economic growth while emphasising environmental stewardship and social responsibility. One of the most substantial benefits is job creation. The mining industry requires a diverse workforce, encompassing engineers, geologists, machinery operators, and support staff, offering both direct and indirect employment opportunities. For every job at a mine, an estimated six additional jobs are supported in auxiliary industries, including equipment manufacturing, logistics, and professional services. This job creation has a powerful multiplier effect, stimulating local spending and benefiting various other sectors.

The importance of the Junior mining companies must be understood; there are far more of these companies that are the vanguard of mining developments, especially in the lesser-known mining jurisdictions that foster the growth of technology in equipment, and themselves are often the target for the major companies wishing to expand their portfolio of profitable assets.

Furthermore, mining operations are significant drivers of economic growth, contributing to GDP, diversifying economies, duties and royalties, direct and indirect taxation, and enhancing productivity. These operations generate substantial tax revenues for governments, sometimes accounting for 20-30% of total revenue in resource-rich nations. The revenue generated, along with direct investments by mining companies, often funds the establishment of vital infrastructure such as roads, schools, clinics, and housing, improving the quality of life for community members.

A downside is that the governments of less developed nations can become dependent on the duties, royalties and taxes levied on the mining companies, which do not always understand that a mining operation has a definitive life and will at some point close.

The other benefits for the local economies include Infrastructure development in areas such as medical, roads, schooling, public health and boosting local businesses. Mining is one of the driving forces behind infrastructure development (constructing roads, bridges, ports, airports, housing, schools and health centres around mining sites) in areas without any infrastructure, where improved living standards, as well as integrating isolated communities into economic and social systems, can be achieved through the creation of employment opportunities for the local population. Mining operations often serve as the economic backbone of many local communities, particularly in remote or underdeveloped regions or economically inactive areas. The influx of mining activities generates stable incomes and creates business opportunities, enhancing local prosperity. Mining companies have a vested interest in the health and welfare of their staff and the local communities to eradicate debilitating illnesses.

2.3. Current Communication Failures and Their Root Causes in the Mining Industry

Despite the critical importance of mining as discussed in this paper and the growing recognition of social licence, the mining industry continues to struggle with effective public communication. These failures are rooted in a combination of historical practices, a technical-first mindset, negativity from the media, global negativity to mining and an underestimation of community dynamics and the digital information landscape.

In some cases, mining companies prefer to be seen and not heard, which is a policy to their own detriment.

2.3.1. Social License to Operate (SLO)

The "social license to operate" (SLO) refers to an unwritten, dynamic agreement granted by affected communities and stakeholders, indicating their acceptance and approval of a mining company's activities in their area. It is not a formal permit but a crucial permission in determining a project's feasibility and continuity, reflecting the community's satisfaction with community involvement in the company's plans and operations.

The SLO is vital because non-compliance with social and environmental requirements can lead to high costs for mining companies, jeopardising operations and possibly even resulting in their cessation of mining activities. Without social acceptance, community resistance can manifest in detrimental forms, such as protests, grievances, and lawsuits, which can halt ongoing operations. Public trust in the mining industry is closely tied to procedural fairness, where community engagement and governance play central roles. This means that communities expect their opinions and voices to be heard and to be respected, and to have opportunities for meaningful participation in decision-making concerning the social impacts around the mining operations.

The importance of local mining communities being able to hold the industry accountable and influence government policy has emerged as a significant trust driver in the development of mining operations. This reflects a shift in public expectations around transparency and local involvement, underscoring that an SLO is not a one-time achievement but requires continuous effort and a transparent relationship between the mining company and the community. The SLO acknowledges that while mining can provide economic benefits, it also impacts living standards and conditions through environmental, social, and economic changes, which may include addressing challenges such as increased immigration, difficulty in homeownership, inflation, and effects on land, water, and food security. Gaining an SLO signifies that a

company has genuinely addressed these concerns and earned the community's trust, aligning with expectations for economic legitimacy and fair benefit distribution.

2.3.2. Lack of Proactive and Early Engagement

A pervasive failure in mining communication is the tendency to initiate engagement too late in the project lifecycle. Companies often begin dialogues after securing exploration permits or once development is already underway. This reactive approach can be costly, as addressing opposition at later stages is significantly more expensive than proactive engagement. The concept of "day zero" communication, where engagement begins the moment a company enters a community, is crucial yet frequently overlooked [25]. Strategic modus of engaging with the leading social authorities is the first important step towards achieving the SLO.

However, engaging with the public at the early stages of project cycles was also recognised recently by the latest draft edition of the Australasian Code for Reporting of Exploration Results, Mineral Resources, and Ore Reserves International Committee (2025).

The latest version of this code states that Environmental, Social and Governance (ESG) factors must be given equal prominence with respect to the application of the other Modifying Factors associated with establishing the extent of resources that can be mined. This requirement does not presuppose mature knowledge for early-stage projects and only requires available and relevant data to be considered, as is the case for all the Modifying Factors. This is also the case for known environmental or social overlays that would preclude further exploration and/ or development.

The average mining project takes approximately 15.5 years from discovery to production, with about 11 years allocated to discovery, exploration, and technical studies [27]. Li (2025) also noted that mines take longer to come into production due to extended exploration, permitting, and financing processes, despite the recent decline in construction time. All mining projects require an Environmental & Social Impact Assessment (ESIA) to be completed, which outlines the responsibilities of the mining company and identifies specific activities that must be addressed. Most important is the social aspect, which requires community consultations on all aspects of the proposed mining operations. Without an ESIA, no mining project will be allowed to be developed. When this extended development timeline is not effectively communicated from the outset, communities can be caught off guard, leading to frustration and disengagement. A fundamental flaw in the industry has been the historical focus on technical expertise rather than social engagement. This lack of early and comprehensive understanding of a community's historical context with mining, its values, and its concerns creates a conducive environment for opposition and delays (Li, 2025).

2.3.3. Over-Reliance on Technical Jargon and "Data Dumping"

Mining companies frequently overwhelm audiences with technical information that is not presented in an accessible manner, a practice often referred to as "data dumping." Miners forget that what is important to them is not necessarily important to the social groups, so styling the release on information that addresses local requirements is an obvious tactic to be employed. Linguistic analyses of mining presentations reveal that the average communication contains 23 technical terms per page that are unfamiliar to general audiences, requiring a university-level education to comprehend (Zadeh, 2025). This immediate disconnection creates a significant barrier to understanding and engagement.

The root cause of this issue lies in the industry's deep-seated technical expertise, where professionals are accustomed to communicating with peers who share their specialised vocabulary and knowledge base. However, this approach fails when addressing the broader public, who often lack the necessary context and technical background. The consequence is an information vacuum, where companies fail to effectively communicate their own narratives, allowing others, often with dangerous inaccuracies, to control the narrative.

It is reasonable to conclude that the mining sector is ignorant of what the social groups need to know; this has to be addressed, hence this paper.

2.3.4. Failure to Listen and Adapt to Community Feedback

A significant communication failure occurs when companies either cannot or do not genuinely listen to community feedback and adapt their plans accordingly. When communities feel that their concerns are acknowledged but not acted upon, "*meeting fatigue*" sets in, resulting in disengagement after just three interactions without visible follow-through. This transactional approach (where dialogue does not lead to meaningful action) erodes trust and can swiftly escalate legitimate concerns into formal opposition, typically within just 3 to 6 months.

It is essential to recognise that, while strategies and policies are crucial for mining companies, communities often perceive them as obstructions. Therefore, it is vital to ensure that technical jargon is minimised and simple language is used. Also, communities' requirements vary by region and country, so "*one solution fits all*" has to be avoided.

Rigid project designs that neglect to incorporate community input encounter significantly more opposition. This reflects a fundamental misunderstanding of the concept of social license, which relies on two-way dialogue and a willingness to adapt practices in response to community concerns. Public trust is closely linked to procedural fairness, meaning that communities expect their opinions to be valued and genuine opportunities for participation in decision-making to be available. When companies fail to show responsiveness, they risk losing the community's trust and, consequently, their social licence to operate.

2.3.5. Allowing Others to Control the Narrative

In today's digital age, both positive and negative news spreads rapidly, and a single incident can quickly escalate across social media, investor forums, and news outlets before a company can formulate a response. Mining companies can no longer presume they control the narrative. If they do not proactively tell their own stories, others will, often disseminating dangerous inaccuracies. This creates a "silence spiral," where unanswered stakeholder questions and information voids lead to growing resentment (Zadeh, 2025). For example, many recent mine accidents and incidents around the world were also closely watched by millions of people. Some of these accidents are listed in Table 1.

A lack of preparation, confusing information, and significant delays in providing timely updates can result in widespread community anger and lead to an inquiry. In such situations, social media can fill the information gap but may also contribute to confusion, where community-initiated social media groups can emerge to share self-sourced information due to perceived inadequacy and untrustworthiness of official sources. Trust must be earned daily through transparency, speed, and consistency, especially in high-risk environments where regulatory scrutiny, environmental incidents, and political tensions can arise unexpectedly.

Sharing information and building a reliable trust bank with key members of the local community is essential so that any issues or misunderstandings can be mitigated quickly.

2.3.6. Misunderstanding Community Needs and Power Dynamics

Mining companies often approach relationship-building with local communities in a rather haphazard manner, frequently overlooking reputational trends. Their communication efforts usually focus narrowly on tangible benefits like jobs, contracting opportunities, or funding for community activities. While these benefits are important, they often do not address the deeper, more complex needs and aspirations of affected communities, in part because the community development is well in advance of what the mining company has allowed for.

Communities in mining areas often face challenges such as rising immigration, difficulties in home ownership, inflation, and concerns about land, water, and food security. Indigenous communities, in particular, confront exacerbated issues due to historical marginalisation and profound cultural ties to the land. An effective community relations program must prioritise these unique needs by conducting baseline surveys, performing thorough research into community essentials, and creating plans to manage and address them.

A significant barrier to effective engagement is the power imbalance between resource-rich mining companies (often perceived as outsiders) and underserved communities, which may lack negotiation training, funds for technical/legal advice, or adequate technology to advocate for their interests effectively. This disparity can lead to communities feeling overwhelmed and seeking support from larger organisations to level the playing field. Without direct engagement, involvement, and ultimately consent from Indigenous peoples, mining projects are unlikely to succeed. The failure to conduct one-on-one conversations on the

community's terms further exacerbates this misunderstanding, as many individuals may be reluctant to share their views in group settings.

Table 1. Some major mine accidents captured the attention of the national/international audience in recent years

Year	Country	Operation	Comments
2024	Chile	Copper	A collapse at Chile's El Teniente copper mine killed one worker and left five others trapped. The incident was attributed to a "seismic event," which may have been a naturally occurring earthquake or one caused by mining activity.
2024	Zimbabwe	Gold	A mine collapse at the Redwing mine trapped 15 miners, with their fate initially unknown. This incident drew attention to the risks faced by subsistence miners who often work in unregulated, dangerous conditions.
2024	Türkiye	Gold	A major landslide in February 2024 at a gold mine in Iliç, Türkiye, trapped nine mine workers. The landslide was of particular concern due to the risk of a "cyanide-spillage" landslide impacting the surrounding environment adversely and causing health hazards.
2024	Iran	Coal	A methane gas explosion at a coal mine in Tabas, Iran, killed 50 workers. The accident was linked to a lack of adequate safety standards, with reports indicating that workers had previously alerted management to the smell of methane gas.
2023	China	Coal	A massive landslide at Xinjing Mine in Inner Mongolia killed 53 people. Investigations revealed that the accident was caused by illegal construction, reckless operation, and inadequate supervision.
2023	Kazakhstan	Coal	A fire in October 2023 at Kostenko Mine killed 45 miners, the country's worst mining disaster in its post-Soviet history. The incident led to the nationalisation of the company's local affiliate and widespread criticism of its safety record.
2023	South Africa	Palladium	A fatal accident in November 2023 at an Impala Platinum mine resulted in the deaths of 13 workers, caused by a conveyance shaft failure.
2022	Türkiye	Coal	A mine explosion at Amasra Mine in October 2022 killed 42 people and injured dozens more. The explosion was one of Türkiye's deadliest industrial accidents, and it led to public outcry and a government investigation.
2021	Russia	Coal	In November 2021, a methane explosion at Listvyazhnaya coal mine in the Kuzbass region killed 51 people, including miners and rescue workers.
2020	Myanmar	Jade	A large-scale landslide in July 2020 at the Hpakant Jade mining site in Hpakant killed between 175 and 200 miners. The victims were largely "freelance jade pickers" who scavenge tailings from larger operators. This was Myanmar's deadliest-ever mining incident and underscored the extreme dangers of the country's unregulated and informal mining sector.
2020	Australia	Coal	In May 2020, a methane explosion at the Grosvenor mine in Queensland seriously injured five people. The incident sparked a comprehensive investigation into the mine's safety practices, leading to significant changes in safety protocols within the Australian mining industry.
2019	Brazil	Iron	While not a typical mine accident, the collapse of a tailings dam at the Córrego do Feijão mine in Brumadinho, in January 2019, killed 270 people. The disaster released a massive wave of mining waste, which buried homes, farms, and part of the city. The incident was one of the deadliest industrial accidents in Brazil's history, drawing global attention to the risks associated with tailings dams.
2014	Türkiye	Coal	301 miners killed and 162 injured at Soma Mine. This made it the worst mining disaster in Türkiye's history. A fire, which was reportedly started by an explosion in a power distribution unit, filled the tunnels with carbon monoxide and smoke. Most of the victims died from carbon monoxide poisoning. The disaster happened during a shift change, which contributed to the high number of workers underground at the time.
2010	Chile	Copper-Gold	The Copiapó mining accident was a globally televised event that captivated the world for over two months. The miners were trapped approximately 700 m underground. The rescue involved three separate drilling teams, with international assistance, to create a shaft wide enough to pull the miners out. This was achieved by using a special capsule known as the Phoenix capsule, which was winched down the narrow borehole to bring the men to the surface one by one.
2007	Russia	Coal	110 people were killed in the explosion of the Ulyanovskaya mine on 19 March. This made it Russia's deadliest mining accident in more than a decade. A blast of methane gas/coal dust caused the explosion. Investigations revealed that safety equipment, including CH ₄ sensors, was deliberately tampered with to increase coal production. <i>The first author of this paper and his team were also involved in inspecting the mine at the time the accident occurred, in which a British colleague (Ian Robertson) was killed along with the mine's senior management.</i> The disaster exposed systemic safety violations and a disregard for regulations in the drive for production. The incident led to a public outcry and a criminal investigation, which resulted in the dismissal of several mine inspectors and officials.

This situation has been addressed by the international mining companies in the form of protocols and policies, which require integration into the local community and engagement with local representatives as a matter of course. The Junior mining companies tend to have a more conciliatory approach in that the owners are often involved at the concept stage of the mine's development, and speaking to the “man” or “woman” is seen as a positive by the community, as they can rightly expect actions to be taken in response.

2.4. A Cradle-to-Grave Communication Framework for Mining Projects

Effective communication for mining projects requires a strategic, integrated, and continuous approach that spans the entire project lifecycle, from initial exploration to post-closure. This framework is built upon a set of overarching principles and tailored phase-specific strategies designed to build and maintain the social license to operate.

2.4.1. Key Principles for Effective Communication

Successful communication in the mining sector is not just about conveying information; it is about fostering genuine relationships, building trust, and ensuring mutual understanding. Originally, the “Seven Cs of Communication” were introduced in a book in 1952 (Cutlip and Center, 1952): Courtesy, Clearness, Conciseness, Correctness, Concreteness, Consideration, and Completeness.

Despite the list being catered to improve professional communication skills, particularly within the advertising industry and while some of the names have been slightly altered or replaced in modern interpretations (for example, “clearness” is now commonly referred to as “clarity” and “consideration” has been replaced by “coherence”), the fundamental principles remain a cornerstone of effective communication in a wide range of business, marketing, and communication contexts. Presentations should avoid gimmicks and automations as these detract from the messages being made and may be viewed with suspicion by the local community.

The mining company must understand the goals of the communities that will be “touched” by the mining operations, as there is often competition between villages for jobs and investment in infrastructure. The mark of success can often be worlds apart between mining companies and communities, where success is measured in livestock, not shares!

This list can be adopted into the mining projects in the following ways:

Clarity (Use of simple language): Avoiding technical mining jargon and engineering terms will help to explain complex processes in a way that is easy for a non-professional person to understand. For example, instead of using “...hydro-geological modelling...” in presentations, saying “...studying how the project might affect local water sources...” can make it more relevant. Stating the purpose of the communication upfront and addressing the community's primary concerns directly, such as potential environmental impact, job creation, and land use, will make the message more relevant for the audience to assimilate.

Conciseness (Sticking to the point): During community meetings, it is critical to focus on one topic at a time. Providing short, digestible explanations rather than long, rambling speeches and using visual aids like charts or simple diagrams, or videos will make the message more comprehensible. It is also essential to appreciate that community members are volunteering to receive the message being delivered to them. Keeping presentations brief and allowing ample time for questions and discussion will generate early engagement in the process.

Concreteness (Provision of specific examples): Providing solid, concrete examples will enhance the message's credibility by using relatable comparisons and focusing on a limited number of key points (no more than four) to avoid overwhelming the audience. For instance, rather than simply saying, “...We will protect the environment in our water processing...” it would be more effective to state, “...We will install a water treatment plant that can process X litres per day to ensure all released water meets state environmental standards...”. This approach better conveys the message.

Correctness (Ensuring accuracy): Using verifiable data and facts (e.g., maps of the project area, figures on potential job creation, results from independent environmental studies) will ensure the reliability and positive outcome of the project. If a question is asked that you cannot answer, it is better to say, “...I don't have that information right now, but I will find out and get back to you...” than to guess or provide incorrect information. This will help to build credibility.

Coherence (Structuring the message logically): Organising presentations and information packets clearly will help to comprehend the narrative, such as starting with an overview, addressing concerns one by one, and ending with a summary and a call to action. Maintaining consistency will also ensure that all team members use the same information and key messages. A consistent message prevents confusion and shows a unified front.

Completeness (Provision of all necessary details): Rather than withholding information, the provision of a complete picture of the project, including potential risks and mitigation strategies, not just the benefits, will portray the big picture. For example, including details on the reclamation plan for the site after the mining is complete will help visualise the project's final results. Ensuring that community members know how to access more information, whether through a project website, a dedicated phone number, or a physical community liaison office, will help build communication channels between stakeholders.

Courtesy (Listening actively and respectfully): To demonstrate respect, it is essential to actively listen to the concerns and feedback of community members without interruption, as well as acknowledging their points before responding, as their concerns are valid and arise from a legitimate desire to protect their homes, environment, and way of life. Employing a respectful and empathetic tone in all interactions is non-negotiable. Acknowledging their feelings and expressing gratitude for their input will effectively foster understanding and empathy among everyone involved.

In addition to the key principles above, further core criteria should underpin all communication efforts. Companies need to define their communication objectives and strategies as early as possible, even before sending the technical crews for the field work. This includes setting specific goals for each interaction, whether it is building awareness, correcting misinformation, or soliciting feedback. The selection of communication channels should align with audience preferences, incorporating digital engagement options such as video content and social media. Moreover, measuring communication effectiveness is crucial. This includes tracking community sentiment through regular surveys, analysing media coverage to assess tone and message penetration, and monitoring permitting success rates, as projects with strategic communication often experience fewer regulatory delays. To transform mining communication from a reactive necessity into a strategic asset, several overarching enablers are essential, beyond specific phase strategies. It is important to ensure that there is an opportunity for community involvement in the meeting and presentation, if only to update on previous discussions and key points raised by the community before.

Effective communication starts with a clear, informed plan. Crisis preparedness is a non-negotiable component of strategic communication. This involves developing and rehearsing a crisis management plan that outlines roles, responsibilities, and key messages. It is essential to acknowledge issues swiftly, communicate empathetically to validate emotions, and provide regular updates. Companies should anticipate backlash and foster a culture of transparency, ensuring that internal stakeholders are informed first, which equips the team to support the message effectively.

Commitment and Early Engagement: Demonstrating a commitment to understanding and engaging with the community should begin from "the project start day" as soon as a company is interested in an area. This early dialogue enables companies to grasp the community's historical context with mining and manage expectations regarding timelines, which is crucial given the average 15.5-year development period for mining projects. Proactive engagement helps identify potential issues and opportunities before they escalate, ultimately reducing future costs and conflicts. Sustained information sharing with the local communities is essential, especially during the 15.5 average development period.

Transparency and Accountability: Open and honest communication is fundamental to building trust. This requires addressing issues directly, sharing relevant information in clear language, and providing timely responses to community concerns. Consistency in messaging across all communication channels is vital since mixed signals can erode trust. Most importantly, companies must fulfil commitments made to demonstrate reliability and accountability. In today's digital age, digital resilience, the ability to withstand challenges, respond effectively, and recover, is crucial for any mining company committed to its future. News, both positive and negative, spreads rapidly across social media, investor forums, and news sites. Companies cannot assume they control the narrative; they must earn trust daily through transparency, quick responses, and consistent engagement.

Therefore, consistent messaging across all team members is crucial to prevent contradictory information that can lead to community resistance. Companies must clarify their key values and mission internally before engaging externally, ensuring self-awareness and coherence in all communications. Establishing clear communication channels, particularly during crises, is essential for a unified approach. A major barrier to

effective communication is inconsistent messaging, often stemming from a lack of internal clarity and training. Therefore, company-wide communication training is essential to ensure all team members, particularly technical professionals, who frequently serve as the first point of contact with communities, understand the social implications of their work.

A clear chain of command for communication is vital to prevent contradictory messaging and ensure a unified voice. Employing dedicated community relations specialists who can engage directly with community residents, access and interpret information, and act as a liaison can significantly enhance communication effectiveness, especially during high-pressure situations. This recognises that operational staff and communication departments in head offices may be remote from where emergencies and concerns arise.

Inclusiveness vs “Us & Them” Mentality: Engagement should foster mutual respect, recognising the rights, cultural beliefs, values, and interests of all community members, especially Indigenous Peoples. This principle involves identifying and engaging a diverse representation of the community, including marginalised groups, and creating appropriate opportunities for participation in decision-making processes. Prioritising the needs and desires of Indigenous peoples, such as conducting baseline surveys and developing plans to address community essentials, is fundamental to this principle. This may also require translators for local languages, as the national language is not necessarily the one spoken locally.

The "us and them" mentality is a natural human tendency to categorise people into groups, leading to a subconscious bias where one's own group is seen as superior and the "other" group as problematic or even adversarial. In the context of large-scale projects like mining, this often manifests as a divide between the company (the "them," often perceived as outsiders focused on profit) and the local community (the "us," protecting their homes, environment, and way of life). This polarisation is fuelled by deep psychological needs for belonging, control, and meaning, which, if not channelled constructively, can lock parties into rigid thinking, distrust and divergence

To bridge this divide and combat the “us & them” mentality and foster a collaborative environment, several common measures can be adopted:

- Blurring the lines and finding similarities (seeking and highlighting common ground and shared values),
- Emphasising shared identity (how the project's success contributes to the community's well-being, or how the minerals extracted are essential for modern life that benefits everyone),
- Highlighting common goals/threats (identifying shared threats (e.g., climate change, economic instability) or common goals (e.g., sustainable development, local prosperity, improved infrastructure)),
- Cultivating empathy and perspective-taking,
- Active listening,
- "Walk a Mile in Their Shoes" (encouraging personnel, especially those in leadership and community-facing roles, to develop empathy and compassion for the community's experiences and concerns).
- Acknowledging historical context (recognising that communities may have historical grievances or past negative experiences with mining or other large projects),
- Empowering collaborative governance and shared decision-making,
- Establishing inclusive structures (implementing collaborative governance structures that include significant and diverse community representation, empowering community members in the decision-making process),
- Joint problem-solving (shifting from an adversarial negotiation style to one of joint problem-solving, where parties work together to generate creative solutions)
- Capacity building (supporting community organisations with strategic advice, financial support, and technical training to help them participate meaningfully in consultations and level the playing field,
- Consistent, transparent, and responsive communication to combat the distrust inherent in an "us vs. them" mindset,
- Openness (sharing updates, data, and explanations of decisions, even when difficult),
- Accountability (admitting mistakes and addressing shortcomings directly),
- Regular feedback loops (seeking feedback through surveys, forums, and one-on-one conversations and visibly integrating this feedback into project plans).

Dialogue and Responsiveness: Genuine two-way dialogue is essential, meaning companies should prioritise listening over talking and ensure that the right people represent them in the meetings, i.e. they listen properly. Additionally, understanding your audience is essential to ensure that the messages being conveyed are those that are received. This involves seeking, listening to, and considering community feedback and, most importantly, using that input to improve decision-making. Taking responsive action following dialogue, such as adapting project plans based on community input or providing proactive infrastructure support, is critical to preventing "meeting fatigue" and building credibility.

2.4.2. Phase-Specific Communication Strategies for Mining Projects

Effective communication should adapt to the evolving needs and concerns of communities throughout the different phases of a mining project's lifecycle.

In today's digital landscape, companies are finding innovative ways to enhance engagement and transparency. One effective approach is through the use of digital platforms. By maintaining an active presence on social media networks like Facebook, LinkedIn, and Instagram, businesses can share updates and interact with community members in real-time. This presence not only allows for immediate feedback but also helps companies monitor social media hashtags and mentions, enabling them to identify trends and quickly address any misinformation or negative perceptions that may arise.

Moreover, visual communication has become a powerful tool for conveying complex technical information. Companies are increasingly transforming this information into accessible insights through infographics, charts, graphs, and maps. By utilising both static and interactive tools, businesses can facilitate data exploration, pattern recognition, and effective information dissemination, ultimately promoting more informed decision-making among their stakeholders.

Additionally, the integration of real-time data and dashboards plays a crucial role in modern business communication strategies. Companies are leveraging communication mining tools to extract valuable insights from various channels, including emails, social media, and customer feedback. This approach allows organisations to gauge public sentiment, track service demand, and pinpoint opportunities for improvement. It is important not to overstate the audience in the context of what they know or do not know, or what they want or do not want. As a result, they can generate real-time statistics and alerts to monitor channel performance and identify potential risks before they escalate. This proactive stance not only fosters transparency but also strengthens the relationship between companies and their communities.

Facts and data alone often fail to emotionally engage audiences and foster lasting trust. Storytelling is a powerful tool for shaping public perceptions, building brand identities, and creating connections. When conveying the relatable narration, it is important to tailor the story to the knowledge level, needs and interests of the audience. Keeping it simple and focusing on a clear, straightforward narrative that avoids jargon and overly complex explanations will deliver the message more effectively. Emphasising conflict and resolution will provide a structured approach to the solutions by presenting simple graphs, charts, and images that support the narrative and illustrate and reinforce the key points. It is vital that any image or graphic is explained for what it demonstrates.

2.4.2.1. Exploration & Prospecting (Discovery to Resource Statement)

The initial phase, from geological exploration to defining a mineral resource, is critical for laying the groundwork for a strong social license. The primary aim is to build initial relationships, gather baseline data on the social landscape, and manage community expectations regarding the long development timeline. Engagement should commence the moment a company enters a community, rather than waiting until permits are sought. This includes understanding the community's historical context with mining and its unique social and economic environment.

In the process of comprehensive stakeholder mapping, it can become clear that identifying all relevant parties, including the local population, local businesses and their associations, recreational groups, and historical societies, is essential. Understanding the information sources these groups rely on provides valuable insights.

As the initiative evolves, one-on-one conversations emerge as a vital strategy. These discussions take place beyond the confines of public meetings; instead, opportunities are created for individuals to share their

thoughts in a setting and at a time that suits them. This approach allows for a deeper understanding of the community's priorities and needs.

Conducting baseline surveys and research further enriches the dialogue. Comprehensive investigations into community essentials such as housing conditions and shortages, infrastructure development, and access to medical services highlighted pressing issues that require attention. This groundwork lays the foundation for developing informed plans to address these concerns. To facilitate ongoing communication and connection with the community, the establishment of local information offices becomes a priority. These offices, staffed with local individuals, can foster a consistent dialogue, allowing residents to engage continuously and feel heard. Through these efforts, a more collaborative and informed community partnership can start to thrive.

2.4.2.2. Planning & Evaluation (Technical Studies from Scoping to Feasibility Study)

This phase involves detailed technical and economic assessments of the project's viability, and communication needs to reflect this increased specificity. The objective here is to share detailed project plans, gather specific feedback on potential impacts and proposed mitigation measures, and demonstrate how community input will genuinely influence decision-making.

The strategies may involve many measures to address the local communities' concerns. For example, the community advisory committees/reference groups can be established as formal forums where community representatives, industry experts, and company representatives voice concerns, share ideas, and actively contribute to the decision-making process. Visioning processes engage communities in collaborative exercises to envision post-mining land uses and long-term benefits, incorporating diverse knowledge and values into planning. Social Impact Assessments (SIA) for mine closure can be conducted with a specific focus on the social implications of mine closure from the outset, ensuring that community input plays a vital role throughout the assessment. Transparent royalty and benefit-sharing agreements can also be implemented with profit-sharing models and community benefits agreements (CBAs), which ensure communities receive a fair and proportional share of benefits from resource extraction. These agreements go beyond regulatory minimums and address community-identified issues. Project adaptations can demonstrate responsiveness by visibly altering project plans based on community input.

This phase proves critical for demonstrating procedural and distributive fairness, which serve as key drivers of public trust and acceptance. Companies show that community input is not only collected but genuinely considered and integrated into project design.

2.4.2.3. Construction (Site Preparation to Commissioning)

This phase marks the physical onset of the project, resulting in immediate, tangible changes to the local environment and community. The objective here is to manage immediate impacts (e.g., noise, traffic, population influx), provide regular updates on progress and timelines, and proactively address emerging concerns.

Many strategies can be adopted for this phase. For example, regular, proactive updates provide consistent information on construction milestones, potential disruptions (e.g., blasting schedules, increased traffic), and safety measures through multiple channels (e.g., newsletters, community meetings, dedicated hotlines, social media). Addressing local impacts can involve acknowledging and communicating plans for mitigating specific impacts such as noise, dust, and truck traffic. Proactive infrastructure support can involve an investment decision and communicating support for community infrastructure that may be strained by population influx, such as schools, healthcare facilities, and housing. Informing the employment opportunities to the local communities and contracting updates can improve the relationship with the community to demonstrate tangible economic benefits during this active phase.

This phase tests the commitments made in earlier stages. Consistent, transparent communication, combined with visible actions to address concerns, is essential to maintain the trust established and to prevent opposition. Developing a two-way street is crucial to structured and sustained communications. Allowing flexibility in communication meetings with communities is important as it presents a little informality and can be expected to result in open and frank discussion.

2.4.2.4. Operations (Steady-State Production)

The operational phase is often the longest, spanning decades, and requires sustained, long-term relationship management. The objective here is to maintain long-term positive relationships, continuously demonstrate ongoing benefits, proactively manage issues, and articulate the broader societal contributions of the mined materials.

Strategies may include many project-specific measures. For example, a well-planned continuous community engagement programme is to maintain established engagement channels (e.g., community committees, information offices) for ongoing dialogue, feedback, and issue resolution. Sustainability reporting should transparently disclose efforts towards sustainable practices, including environmental impact assessments, community development programs, and initiatives to minimise carbon emissions and promote renewable energy sources. A proactive crisis management plan should include robust crisis communication plans, including clear roles, responsibilities, and key messages, to address any incidents swiftly and empathetically. Regular updates and accountability are crucial during crises.

Showcasing broader societal contributions, such as how the extracted minerals contribute to modern technology, healthcare, and infrastructure, connecting the mine's output to everyday products and global advancements, should be regularly communicated back to the community and society.

Mining companies can also use digital marketing to improve their public image. Campaigns could highlight the essential role of minerals in everyday life and for a low-carbon future. Marketing efforts can also emphasise environmental stewardship, safety, and community benefits. Companies can use various channels, from social media to SEO, to showcase their technological advancements, philanthropic contributions, and commitment to sustainable and responsible operations. The marketing concept should embrace the involvement of the community to demonstrate collaboration.

Mining companies often engage in community development projects, including education and training, as a part of their CSR. This can include sponsoring local events, building infrastructure like roads, or supporting health and education initiatives. However, research suggests that communities often feel they do not benefit proportionally from mining operations and may lack a voice in how these programs are run.

The mining industry has been known to fund local arts and sporting events to support the local communities. While these initiatives are often framed as community support, some critics argue they are primarily used to gain a "social license to operate" and improve the company's reputation. This demonstrates the complexities of relations between the mining company and the local community and the level of understanding of the local communities.

Museums are also a common way to showcase the history and importance of mining. The Ruhr Museum in the former coal washing plant on the Zollverein World Heritage Site in Germany, the Zonguldak Mining Museum, Cankiri Salt Rock Mine Museum in Turkey are some good examples.

3. Discussion/Conclusion and Recommendations

The ongoing communication gap between mining companies and the public represents a significant strategic challenge that directly affects the industry's social license to operate and its ability to contribute effectively to global development and the energy transition. Analysis indicates that this gap arises from a combination of late and reactive engagement, an over-reliance on technical jargon, a failure to understand the local community genuinely, and therefore a lack of listening and adapting, as well as an inability to proactively manage the narrative.

In mining projects, a different range of experts (e.g., from engineers and geologists to machinery operators and support staff) is involved in the projects, and they also interact with the local population daily as a part of their operating roles. Therefore, visible leadership is essential in communication at grassroots levels whilst conducting professional duties. Hence, the training aspect is essential for all experts interfacing with the local community.

Another aspect is the continuity of the individuals who are regularly visible to the local population. Change of personnel at the company level, who do not understand the local dynamics and will take time to grasp these dynamics, may also cause additional frictions and resentment. Local communities typically want to see one champion from the company side who understands their needs.

To bridge this divide and encourage societal acceptance of mining's necessity, a fundamental shift in communication philosophy is essential. This shift requires moving beyond mere transactional information dissemination to a relational, empathetic, and continuously engaged approach that encompasses the entire project lifecycle.

Another avenue is to learn from the Australian population's attitude to mining, where the public perception is generally positive and balanced because it is engaged and informed [2]. The CSIRO survey highlighted that trust elements towards mining include:

- consistency over time in the relationship levers (i.e., trust in the mining industry acting responsibly increases, hence the acceptance),
- procedural fairness (i.e., community members feel the mining industry listens to and respects community opinions, is prepared to change its practices in response to community concerns and provides opportunities to participate in decisions about mining, hence more community trust in the mining and acceptance of its activities),
- confidence in governance (the capacity of governments, legislation and regulation, to hold the mining industry accountable and ensure it operates in line with its obligations),
- environmental impacts (e.g., the more negative environmental impacts Australians associate with the mining industry, the lower their trust in it),
- confidence in local mining communities to hold the industry accountable and influence mining-related government policy,
- and distributional fairness (e.g., Australians feel their country and the communities directly impacted by mining receive a fair share of the significant benefits generated by the mining industry).

Considering the aforementioned discussion, the mining industry needs to adapt to the modern era by employing different tactics and strategies to convey the message on the necessity of mining to society. Therefore, the industry is in a transitional phase to position and prepare itself strategically for Industry 4.0.

As the mining industry is global, we need to check what has worked and not worked for others and learnt from the mistakes and positive outcomes. A good communication network is essential to tap into each other's experience pool. If necessary, a talented communication team needs to be engaged by the industry representatives to figure out how to communicate with society at the global and local levels, understanding what the idiosyncratic requirements of specific communities are.

Some of the recommendations for the mining sector to communicate better with the public are:

Global/Wider Level:

- Constant advertisement campaigns through traditional venues (radio, TV, printed media) and social media outlets (Facebook, Instagram, BlueSky, X, Telegram, TikTok, LinkedIn, etc.) to highlight the necessity of mining for our daily lives.
- Appointing celebrities, public, and industry faces to promote mining actively,
- Financing movies, TV series, theatre pieces and documentaries promoting a mining storyline,
- Emphasising the relatable narrative message back to the society that the mining industry is an essential part of the local community and national economy to break the "us vs them" mentality,
- Being visible in public forums, panels to advocate for the mining activity,
- Participating in the public debates constructively and collaboratively to engage with the mining opponents,
- Rather than being confrontational, emphasising the necessity of mining and recognising the impact generated by the industry and highlighting the mitigation measures actively taken against these impacts regularly (the showcase examples to be demonstrated constantly),
- Humanising the industry through personal stories (featuring mining professionals and their motivations) to connect with the public. Proactively managing the narrative and leveraging storytelling will help them to tell their own stories accurately. This will lead with compelling narratives that humanise the industry, emphasising the perseverance, scientific investigation, and personal stories behind mining projects.
- Connecting the dots between mining, everyday products, and global advancements, illustrating mining's indispensable role in modern life, technology, and the energy transition, will highlight the importance of the industry in everyday life. A great example of this is the Mining Magazine of Türkiye's junior edition, which is distributed free of charge to primary schools.
- Promoting mining through sponsorship of bursaries for education and training for talented individuals and local communities to upskill the current workforce and attract new talent. Programs can also focus on partnering with and providing education to Indigenous/local communities.

- Exclusive galas, sponsoring major art and sporting events attended by local and national celebrities, public figures, reality stars, industry leaders and politicians to improve the industry's image and promote mining and its positive contribution regularly.
- Providing financial support and sponsorship for the local mining/geological museums to improve visibility and acceptance,
- Plain language in all communications, but avoiding technical jargon.

Local Level

- Preparation of an engagement and communication plan for the company personnel to use throughout the project should be in place for the project.
- Building internal communication capacity and alignment will establish clear lines of communication and ensure internal alignment to prevent inconsistent messaging, which significantly erodes public trust.
- Implementing company-wide communication training, particularly for technical professionals, to equip them with the skills needed to engage effectively with diverse public audiences. Training and visible leadership in communication at the grassroots levels should be provided for all front-line personnel. It is imperative that all team members, particularly technical professionals, understand the social dimensions of their work.
- This training should go beyond just conveying facts and figures; it needs to equip personnel with the skills to translate technical jargon, practice active listening, communicate empathetically, ensure consistent messaging, understand local dynamics, visible leadership, set the example (i.e., leaders "walking the wellness talk" or engaging directly with communities sets a powerful example for their teams), empower staff, prioritise community relations (by incorporating community engagement metrics into key performance indicators (KPIs) and discussing them in safety briefings, leadership signals that effective community interaction is a core business responsibility).
- Prioritising early, continuous, and inclusive engagement and communication from the project "start day", initiating dialogue as soon as a company enters a community.
- Making sure that all essential paperwork, permissions, licensing documents, personnel documents (driver's licence, car registration documents, company appointment letters, etc) and necessary approval procedures from both local and regional authorities to mobilise the technical crews to the field are in place before the team is on site.
- Through one-on-one conversations, conducting comprehensive stakeholder mapping to identify all affected groups, including indigenous and local communities, and tailoring engagement methods to their unique needs and preferences are critical to establishing a positive relationship and communication process.
- Fostering genuine two-way dialogue by actively listening and acknowledging legitimate concerns rather than dismissing them, and demonstrating responsiveness by adapting project plans based on community feedback to achieve a higher persuasiveness rating.
- Continuity of personnel interacting with the local community to ensure that the community's desire a consistent "champion" from the company side. Frequent personnel changes can indeed cause friction and resentment, as they disrupt the trust and understanding built over time, since the understanding of local dynamics takes time. New personnel, unfamiliar with the local context, history, and specific community dynamics, will take time to grasp these nuances. This learning curve can lead to misunderstandings, repeated questions, and a perception that the company is not genuinely invested in the relationship. Communities often feel that their concerns are not being adequately addressed when they have to re-explain issues to new contacts. Therefore, providing a consistent point of contact serves as a stable, familiar face for the community, fostering trust and a sense of reliability.
- Dedicated roles like Community Liaison Officers (CLOs) are critical for providing this much-needed continuity. CLOs act as a primary point of liaison between mine operators and local communities, managing relationships with residents, landholders, businesses, and organisations. Building long-term relationships will provide effective community engagement in the long term. Trust is established through transparency, open communication, and consistently delivering on commitments. When personnel change frequently, this continuous relationship-building is undermined.
- Investing in plain language and visual communication is paramount. This will act as a "translation tool" for technical information by contextualising data and breaking down complex numbers into

relatable comparisons. Eliminating industry jargon in public-facing communications through prioritising visual communication (infographics, charts, videos) will ensure that content is accessible to a general audience to enhance comprehension and retention of complex information.

- If necessary, presenting the mine project and all auxiliary components in a model printed on a 3D printer should help to visualise the project for the local population. Alternatively, the use of reality augmented glasses may also help to visualise the project components and impacts.
- Engaging local communities in marketing initiatives so that they can be seen taking part and contributing to the overall mining ethos.

By strategically integrating these communication principles and practices throughout every phase of a mining project's lifecycle, the industry can evolve from merely obtaining permits to genuinely earning and sustaining its social license to operate. This proactive, empathetic, and transparent approach is not just a public relations exercise; it is a strategic necessity for mitigating risk, fostering societal understanding, and ensuring the long-term viability of an industry crucial to global progress.

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Financial Models in the Rehabilitation of Abandoned Mine Sites: Case Studies from the World and Turkey

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Abstract

Mining is a sector that utilizes non-renewable natural resources, and the technologies applied during ore production can lead to significant degradation across three main components: the physical, biological, and social environment. The high number of abandoned mine sites worldwide and in Turkey makes the restoration of these areas to nature a critical environmental and societal issue. An effectively planned rehabilitation process not only ensures environmental recovery but also generates positive economic and social impacts. One of the key elements of a successful restoration process is financial management. Financial models not only serve as a guide for public and private sector investors but are also among the primary factors determining the feasibility of projects. Due to differences in the economic and institutional structures of countries, rehabilitation financing models vary by country and even on a regional scale. This study examines financial assurance mechanisms that secure rehabilitation/closure obligations. Financial models successfully implemented worldwide for the restoration of completed mining sites are compared with current practices in Turkey, and a comparison matrix is developed; based on this, a risk-based hybrid approach is proposed for Turkey.

Keywords; Financial models, Mine rehabilitation, Rehabilitation financing, Abandoned mine sites.

1. Introduction

Population density is increasing in parallel with the acceleration of technological advances in developed and developing countries; accordingly, energy demand and urbanization requirements are also increasing significantly. It is observed that investments in the mining sector are increasing gradually in order to meet the increasing energy needs. However, mining activities lead to environmental destruction during and after the extraction of natural resources. For this reason, it is of great importance that mining sites are treated within the framework of a planned and holistic life cycle approach from the beginning of the utilization process to the end of their economic life. The regulatory works carried out in mining areas that have completed their economic life are called rehabilitation (post-mining), and this process is an integral and critical component of mining activities. As a result of mining activities, it is inevitable that various damages will occur in physical, social and biological areas. For this reason, it is of great importance to restore the functionality of the areas in question. In order for rehabilitation processes to be carried out effectively and sustainably, financial management stands out as one of the most decisive elements.

Although the mining sector has an economically important position in Turkey, it is observed that the applications for the rehabilitation of mining sites have not developed at an adequate level. In our country, according to MAPEG official data for the year 2025, the number of license applications was recorded as 2,355 units. (MAPEG, 2026) The number of licenses abandoned during the same year was determined as 941 units, and the number of rehabilitated sites until February 1, 2026 was determined as 194 units. (MAPEG, 2026) These data reveal that rehabilitation studies after mining are insufficient. One of the main reasons for

this situation is that the financial planning related to rehabilitation processes cannot be structured in an effective and sustainable way.

Financial models are among the important tools that directly affect the viability of projects by being a guiding feature for both the public and private sectors. Due to the differences in the economic and financial conditions of countries, these models may vary by country and even region. Although there are various studies on rehabilitation projects in the literature, it is noteworthy that studies on how financial management, one of the most critical elements of this process, is structured, are limited. Within the scope of this study, financial models successfully applied worldwide in the restoration of mining areas where production activities have ended have been compared with existing practices in Turkey; suggestions for the effective adaptation of appropriate financial models to the country's conditions have been developed by revealing weaknesses specific to Turkey.

2. Materials and Methods

This study is a qualitative narrative review research prepared for the evaluation of rehabilitation processes after mining activities. Within the scope of the study, both academic literature and national and international legislation documents were examined with a systematic approach.

The literature search was carried out in Web of Science, Scopus and Google Scholar databases. During the screening process, the keywords “mine rehabilitation”, “mine closure”, “land reclamation”, “post-mining land use” and “mining rehabilitation” were used. Publications published between 2000 and 2026, included in peer-reviewed journals and directly related to the subject were included in the study.

Within the scope of the legislative analysis, the Mining Law in force in Turkey and the Rehabilitation Regulation on Mining Sites, which came into force accordingly, were examined in detail. In addition, policy documents and academic studies related to mining rehabilitation practices in Canada and Australia were also included in the analysis in order to make a comparative assessment.

The data obtained in the study were evaluated by thematic analysis approach, which is one of the qualitative data analysis methods. In this context, rehabilitation processes were classified under the headings of financial mechanisms, technical applications, audit systems, stakeholder participation and long-term monitoring and a comparative analysis was performed between countries.

Among the inclusion criteria; the study is directly related to mining rehabilitation, has scientific validity and the full text is accessible, while Decontextualized, repetitive or methodologically inadequate studies are excluded from the analysis. Thanks to this method, the study was placed in a systematic and comparative evaluation framework.

3. Results and Discussion

The concept of environment is defined as the physical, biological, social, economic, and cultural medium in which humans and other living beings maintain their relations and interact throughout their lives. Environmental pollution, on the other hand, primarily manifests as air, water, soil, noise, and visual pollution, affecting the entire ecosystem.

Mining activities belong to a sector that utilizes non-renewable resources. The technologies used during ore extraction can, over time, lead to degradations in the three core components of the environment: the physical, biological, and social spheres. Mining is fundamentally carried out in two ways: open-pit mining, applied when mineral deposits are exposed on the surface (outcrop) or are near the surface; and underground mining, used when the mineral is located deep underground. In our country, coal, metallic minerals, and solution mining can be given as examples of underground mining. The most prominent environmental impact of this method is surface subsidence. In open-pit mining, effects such as the pits formed, changes created by waste rock (overburden) sites in the environment, and issues like dust, noise, waste management, and water pollution arising during ore preparation and enrichment processes are more pronounced. This situation stems from production activities being carried out directly on the surface.

Mining operations are generally conducted in three basic stages: exploration, operation, and closure. In the first stage, exploration, environmental impacts are usually minimal. The operation stage is the phase where the mineral is extracted and enrichment processes are performed; during this process, environmental impacts begin to emerge either positively or negatively.

Once the mining site completes its economic life, the closure phase begins; however, the environmental effects of the site and its wastes can persist for many years. Although these effects are often permanent, they can be mitigated through various methods, and the site can be reclaimed for nature. Within the scope of Environmental Impact Assessment (EIA) reports and operational projects prepared before activities commence, the potential environmental impacts of the site are analyzed to decide whether it should be utilized. In this process, projects are mostly examined from a technical perspective, concrete impacts are identified, and necessary measures are determined (Crookes and deWit, 2002). Situations that may pose a risk to the environment are put under guarantee. However, while these evaluations are made, the economic dimensions of the activities are often not sufficiently taken into account (Demirbugan, 2014). In the study conducted by Delibalta (2012), the environmental and economic dimensions of the mining sector were handled together; the rehabilitation of abandoned mining sites was examined from both environmental and economic perspectives, and sample costs were presented.

However, today, it is observed that studies remain insufficient due to the fact that rehabilitated sites are fewer compared to abandoned sites. Among the primary reasons for this situation are the lack of sufficiently developed sustainable financial methods and deficiencies in the supervision of practitioners.

3.1. Reclamation

It takes a considerably long time for areas degraded as a result of mining activities to return to their former productive state through natural processes. For this reason, the improvement of these areas within a reasonable timeframe encompasses a long-term process aimed at increasing productivity, re-establishing ecological balance, providing economic benefit, and restoring aesthetic values. The methods preferred during the implementation phase vary depending on the characteristics of the terrain, soil structure, socio-economic conditions, and the economic status of the financial resource providers.

The terminology used within the scope of reclamation is presented in Table 1. Furthermore, since the reclamation process is a high-cost and long-term liability, it is of great importance to conduct comprehensive financial planning from the early stages of the projects.

Table 1. Terminology for Post-Mining Land Use

Concept	Description
Restoration	The process of physically, chemically, and biologically returning abandoned mine sites to their original, pre-mining state.
Reclamation	The process of improving the quality of abandoned mine sites in terms of air, water, and soil regimes.
Remediation	The process of rectifying issues occurring at abandoned mine sites to ensure they no longer pose a threat to human and environmental health.
Rehabilitation	The process of transforming abandoned mine sites into a suitable and productive state in terms of the three main pillars: physical, biological, and socio-economic environments.

3.2. Financial Models and Their Applications Worldwide

The total land area utilized for mining activities worldwide has been measured and is estimated to be 101,583 km² (Maus et al., 2022). This corresponds to approximately 0.07% of the total global land area. For comparison, urban areas cover about 0.51% of the total land area globally.

The process of improving areas degraded as a result of mining and similar land-use activities is expressed in the literature through various terms such as "rehabilitation," "reclamation," "reconstruction," "remediation," "restoration," and "revegetation." In Australia, the terms "rehabilitation" and "restoration" are generally preferred to ensure compliance with the National Standards for the Practice of Ecological Restoration (SERA). The financial assurance instruments used worldwide can be classified as shown in Table 2.

Table 2. Financial Assurance Instruments

Category	Instrument	Evaluation (Pros & Cons)
Instrument-Based	Letter of Credit /Cash Guarantee	Pros: Most advantageous for the mining company; capital is not tied up, easy to manage, and financial reports are public. Cons: Even large companies can go bankrupt; financial data can be manipulated, creating a trust issue for the public.
Instrument-Based	Insurance Policy	Pros: Low cost for small companies; does not tie up capital, and cash outflow is low. Cons: Very few options available in the market; major insurance companies are often reluctant to assume environmental risks.
Instrument-Based	Letter of Credit (Bank Guarantee)	Pros: Relatively cheap to set up, does not tie up capital, requires low cash outflow; administrative burden is low, and the state can limit risk by selecting appropriate banks. Cons: The bank itself may go bankrupt; it reduces the company's borrowing capacity and is dependent on market conditions.
Instrument-Based	Surety Bond	Pros: Generally low cost and does not tie up capital. Cons: Risk of the surety provider's bankruptcy in the long term; costs can be high for smaller companies.
Calculation-Based	Cash Deposit	Pros: Can be used directly for rehabilitation; high liquidity and one of the most reliable methods for the public; suitable for small companies and can be transferred to pool funds. Cons: Large amounts of capital remain tied up for long periods; risk of misuse or diversion for other purposes by the public sector.
Calculation-Based	Trust Fund	Pros: High public trust; can increase in value through investments. Cons: Risk of depreciation and management can be complex.

3.2.1. Australia

In Australia, the management of mining activities falls under the jurisdiction of the states. Each of the seven states and territories (New South Wales, Western Australia, Queensland, South Australia, Victoria, Northern Territory, and Tasmania) has its own mineral closure legislation and detailed guidelines specific to its jurisdiction. Financial assurance systems implemented across all states aim to manage long-term environmental risks and establish a safe and stable final landform. Although guarantee mechanisms vary between states, it is mandatory to submit financial assurance to the relevant regulatory bodies during the licensing stage.

According to Australian Government (2016) data, the following elements are of critical importance in these cost estimations:

- Basing costs on data from independent third-party contractors rather than in-house company calculations.
- Making estimations based on the current year's exchange rate and generally securing the highest risk value over the plan period.
- Including post-closure maintenance and monitoring costs in the calculations.

Financial guarantee systems throughout Australia operate within the framework of specific common principles. Guarantees are submitted before activities commence, usually in the form of cash or bank letters of credit, and are inaccessible to the operator. These amounts are periodically updated based on changes in the mine plan and technological developments. The return of the guarantee is only possible once the regulatory authority confirms that the rehabilitation targets have been successfully completed.

In Western Australia, the Mining Rehabilitation Fund Act (MRF Act), which came into effect in 2012, established a non-refundable pooled fund. This system is a centralized financing mechanism aimed at

generating resources not only for active projects but also for the rehabilitation of abandoned mine sites. In Queensland, the Financial Provisioning Scheme, which came into effect in 2019, is a hybrid system that utilizes both a pooled fund and a risk-based surety mechanism. In this model, while low-risk projects are included in the communal fund, high-risk projects are required to provide additional financial assurance.

3.2.2. Canada

In Canada, mine rehabilitation is a responsibility shared between the federal government and provincial/territorial administrations. At the federal level, Natural Resources Canada (NRCan) develops strategic policies, while in regions north of the 60th parallel, oversight is conducted directly by Crown-Indigenous Relations and Northern Affairs Canada (CIRNAC). Nevertheless, the management of mining activities primarily falls under the jurisdiction of the provinces. The province of British Columbia is one of the earliest regions to mandate financial assurance, and guarantees there are reviewed every five years. In the Northwest Territories, the process is carried out through a partnership of federal and local institutions, utilizing a specialized software tool called RECLAIM for cost estimations.

The rehabilitation of orphaned or abandoned mine sites in Canada is addressed under the coordination of NOAMI (National Orphaned/Abandoned Mines Initiative), a multi-stakeholder national initiative launched in 2002. Supported by NRCan and Mines Canada, this structure is a collaborative platform that brings together federal and provincial agencies, mining sector representatives, Indigenous communities, and non-governmental organizations. The financing of orphaned and abandoned mines in Canada is managed through a multi-component model that does not rely on a single source. In this context, the financing structure generally consists of the following elements:

- **Public Budget:** Especially for high-risk sites where no responsible operator can be identified, rehabilitation costs are covered directly from federal or provincial budgets.
- **Sectoral Contributions and Taxes:** Financing is provided through taxes, levies, or specialized fund mechanisms collected from the mining sector.
- **Public-Industry Partnerships:** Joint models, where public institutions and the private sector provide financing together, are implemented for large-scale and complex sites.

Particularly in regions such as Yukon and the Northwest Territories, the cleanup of large-scale abandoned mine sites is carried out under specialized programs managed by the federal government.

3.2.3. Turkey

The process of restoring sites where mining activities have concluded in Turkey is based on a comprehensive structure centered on both ecological restoration and social sustainability. Successful rehabilitation projects implemented across the country not only support environmental rebirth but also contribute to social welfare by creating new economic opportunities for local communities. To ensure these processes are carried out effectively, Turkey has developed robust legal and institutional approaches regarding the management of abandoned mine sites.

The legal frameworks established by the Ministry of Environment, Urbanization and Climate Change aim to ensure that sites regain their environmental, economic, and social functions following the completion of mining activities. One of the most critical mechanisms developed in this context is the guarantee (collateral) application. This system, which is activated during the licensing or permitting phase, is operated to compensate for potential environmental damages caused by mining activities and to guarantee the post-operational rehabilitation of the area.

The guarantee amount is not a fixed figure; it is determined based on variables such as the scale of the activity, type of mineral, methods used, and the current characteristics of the land. Environmental sensitivities, such as the site's proximity to protected areas, play a decisive role in calculating the guarantee amount. These financial assurances, requested by the Ministry or authorized institutions, ensure that environmental risks are kept under control during the operational process and secure the necessary resources to restore the site to its natural functions after mine closure.

Table 3. Reclamation Processes According to Land Characteristics

Land Category	Process and Legal Framework
Agricultural Lands	Following the completion of EIA (Environmental Impact Assessment) processes, a Soil Protection Project must be prepared within the framework of the Law on Soil Conservation and Land Use (Law No. 5403).
Pasture/Grazing Lands	Pursuant to the Pasture Law (Law No. 4342), an application for "Change of Purpose" must be submitted through MAPEG (General Directorate of Mining and Petroleum Affairs), and a Pasture Restoration Project must be prepared.
Treasury Lands	A Land Reclamation Project (Rehabilitation Plan) must be prepared for the relevant projects as part of the operational requirements.
Forest Lands	A Forest Rehabilitation Project must be prepared and submitted to the OGM (General Directorate of Forestry). The OGM issues decisions regarding trees to be felled during the operational phase; the operator must pay for the felled timber and use-of-rights (usufruct). Additionally, the license holder must provide a commitment to plant five times the number of trees felled.

It is a legal requirement for operators active within mining license areas in Turkey to pay various fees to different public institutions, depending on the ownership and usage status of the land they utilize. These obligations aim not only to ensure the environmental compliance of mining activities but also to compensate for the economic losses arising from the land's previous intended use. The most fundamental payment in this context is the Environmental Compliance Fee, determined in accordance with Article 14 of the Mining Law No. 3213. This fee, collected by the General Directorate of Mining and Petroleum Affairs (MAPEG), is calculated annually at a rate of 30% of the operating license fee. However, in addition to this general obligation, there are costs that vary according to the characteristics of the land.

If the activity area is classified as forest land, the General Directorate of Forestry (OGM) requests fees for afforestation, soil value, and a guarantee, taking into account criteria such as the canopy cover of the site and the tree species. Nevertheless, for small areas under 5 hectares, only the afforestation fee is collected, offering a simpler cost structure. On pasture lands, a "grazing fee" (ot bedeli) is collected by the Provincial Directorate of Agriculture and Forestry to compensate for the loss in livestock activities. This amount is based on technical data such as the productivity of the land, the market value of dry hay, and the size of the affected area.

Similarly, a non-agricultural use permit fee is paid for agricultural lands to cover the loss of agricultural production; whereas for activities conducted on Treasury properties, permit and easement (usufruct) fees are accrued by the National Estate units. For Treasury lands, this fee is generally determined annually between 1% and 3% of the property's current market value. To materialize this cost structure, average cost estimates based on different land characteristics for a 5-hectare section of a 50-hectare limestone quarry located in Ankara have been presented with a detailed breakdown.

Table 4. Average Fees Payable to Institutions Based on Land Characteristics

Land Type	Authorized Institution(s)	Average Fee (for 5 ha)
Forest Land	MAPEG + General Directorate of Forestry (OGM)	1,250,000 TL
Pasture Land	MAPEG + Provincial Directorate of Agriculture / Pasture Commission	375,000 TL
Agricultural Land	MAPEG + Provincial Directorate of Agriculture + Provincial Directorate of Environment and Urbanization	500,000 TL
Treasury Land	MAPEG + Provincial Directorate of Environment, Urbanization, and Climate Change	300,000 TL

Land costs for enterprises operating in mining license areas vary significantly depending on the legal status of the land utilized. Cost analyses clearly demonstrate that forest lands impose the highest financial burden compared to other options. Afforestation processes, environmental regulation costs, and protection obligations in these areas translate into substantial additional expenditures for operators. Furthermore, the General Directorate of Forestry (OGM) may demand the afforestation of a different region outside the license area in addition to the site's own rehabilitation. Consequently, forest lands are considered the most arduous option in terms of both cost and the reclamation process. In contrast, pasture lands offer a relatively more economical structure, primarily involving grazing fees and change-of-purpose expenses; while Treasury lands, despite low initial costs, require strategic planning due to long-term easement and rental fees. The legal framework regarding the reclamation of areas degraded by mining activities in Turkey was shaped for many years by the Mining Law No. 3213 and its secondary legislation. However, the amendments made to the Mining Law in 2025 and the Regulation on Rehabilitation of Mining Sites, which entered into force on January 23, 2026, signal a major paradigm shift. In previous regulations, rehabilitation was handled within a "compliance with the environment" approach, and implementation was largely left to the discretion and responsibility of the license holder.

Under the old system, while rehabilitation obligations were subject to technical and administrative audits, there was no financially robust guarantee mechanism. Indeed, the guarantee and environmental compliance fees applied in the former system remained insufficient to cover actual rehabilitation costs in most cases, leading to serious environmental issues in abandoned sites.

With the new regulation, the rehabilitation process has been transformed from a mere technical obligation into a strong financial and administrative framework. The most striking change in this context is the mandatory collection of a rehabilitation fee, equivalent to the annual operating license fee. It is explicitly regulated (Article 6) that this fee must be collected every year in January, with late payment penalties applied otherwise, thereby making financial obligations concrete and binding.

These fees are held in escrow/special accounts and can only be utilized for rehabilitation activities. Furthermore, it is aimed to prevent depreciation by accruing interest on these funds. This arrangement transforms rehabilitation financing from an uncertain future liability into a pre-secured system.

Another significant aspect of the new regulation pertains to the timing of rehabilitation. While previous practices viewed rehabilitation as a post-operational process, the new regulation adopts the principle that rehabilitation must be carried out concurrently with the start of mining activities, continue throughout the operation, and be completed upon mine closure. This approach aligns with contemporary mining philosophies aimed at preventing the cumulative growth of environmental impacts.

Moreover, the new regulation has made rehabilitation processes project-based and measurable. It is now mandatory for rehabilitation projects to be prepared in accordance with scientific data and engineering principles, including a specific budget and schedule, and to be approved by the relevant administration. This increases the auditability of practices and prevents arbitrary implementations.

Significant changes have also occurred regarding administrative sanctions. In the new system, late interest is applied if the rehabilitation fee is not paid (under Article 6), and sanctions ranging up to license cancellation are foreseen in the final stage. Additionally, if obligations are not met, it is now possible for the administration to carry out rehabilitation activities directly and recover the costs from the license holder.

Finally, the new regulation has introduced a performance-based financial mechanism to the process. It is envisioned that the deposited fees will be refunded upon the full completion of rehabilitation obligations, whereas proportional refunds will be made in cases of partial completion. This serves as a vital tool to incentivize license holders to perform rehabilitation activities effectively.

Furthermore, announcements published by the General Directorate of Mining and Petroleum Affairs (MAPEG) regarding the year 2026 specify the implementation principles for collecting the rehabilitation fee. These announcements clearly outline the collection timing, payment processes, and administrative actions to be taken in case of non-compliance, demonstrating that the regulation includes an application-oriented mechanism rather than just a normative one.

When evaluated together, it is observed that the concept of mining rehabilitation in Turkey has evolved from a "post-activity improvement" approach to an "integrated environmental management during activity" approach. The new system aims to create a more sustainable and auditable rehabilitation model through strong financial mechanisms, increased administrative sanctions, and the requirement for science-based projects.

4. Conclusion

The new approach introduced in the field of post-mining rehabilitation in Turkey, through the Mining Law and the Regulation on Rehabilitation of Mining Sites, represents a significant paradigm shift in terms of integrating rehabilitation into the mining lifecycle. However, limitations encountered in the implementation phase of current regulations indicate that the system does not yet fully align with international best practices and that more refined policy instruments are required. In this context, three main policy axes emerge to enhance the effectiveness of rehabilitation policy in Turkey.

First, instead of the current uniform financial assurance model, a risk-based coefficient system that accounts for site-specific differences should be developed. The approach of equating the rehabilitation fee to the license fee does not distinguish between sites with different ecological sensitivities, production methods, and potential levels of environmental degradation. Yet, as seen in the examples of Canada and Australia, dynamic determination of financial guarantees ensures more accurate pricing of environmental risks and incentivizes operators toward more responsible rehabilitation practices. Accordingly, integrating a risk coefficient model into the legislation—incorporating criteria such as ecological sensitivity, biodiversity value, proximity to water resources, and type of activity—is of critical importance.

Secondly, independent third-party assessments must be made mandatory for determining rehabilitation costs. In the current system, the fact that cost calculations are largely shaped between the administration and the operator raises questions regarding transparency and reliability. The practices of independent costing and guarantee determination implemented especially in Australia offer a structure that is more auditable and closer to market realities. Mandating cost analyses conducted by accredited independent organizations in Turkey will both increase the accuracy of the financial assurance mechanism and reduce the burden on administrative capacity.

Thirdly, instead of focusing solely on the completion stage, rehabilitation processes must be supported by long-term monitoring and measurable performance criteria. In current practice, rehabilitation is often limited to short-term engineering solutions; the restoration of ecosystem functions and the sustainability of biodiversity are not sufficiently monitored. At this point, the "Integrated Closure" approach developed by the ICM (International Council on Mining and Metals) envisages planning rehabilitation throughout the lifecycle and evaluating it with long-term ecological indicators. Similarly, a system must be established in Turkey that evaluates the success of rehabilitation through multi-year monitoring programs, performance thresholds, and adaptive management mechanisms.

In conclusion, while the reforms carried out in the field of mining rehabilitation in Turkey have provided significant progress, for effective environmental recovery, it appears inevitable to adopt a risk-based financial model, institutionalize independent costing mechanisms, and develop a long-term monitoring and performance-oriented approach. This triple policy set will strengthen the implementation capacity of the current legislation and ensure that rehabilitation evolves from being merely a legal obligation into an ecosystem-based sustainable management tool.

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Land Use & Transition in Post-Mining Regions: Governance, Innovation, and Societal Engagement

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Abstract

Post-mining regions face long-term environmental, socio-economic, and spatial challenges that require integrated and interdisciplinary approaches to support sustainable transformation. The Research Center of Post-Mining at the University of Applied Sciences Georg Agricola (THGA) addresses these challenges through coordinated research spanning mine water management, geomonitoring, material sciences, and land-use transformation. This paper highlights the contributions of the Land Use & Transition department, which focuses on the political, legal, and societal frameworks necessary for the successful reactivation of former industrial sites and infrastructure, with a specific emphasis on coal regions undergoing structural changes. The research portfolio combines successfully completed and ongoing European projects. Completed projects, **POTENTIALS**, **WINTER**, and **GreenJOBS**, demonstrate mainly forward-looking business models for the post-mining regions, while **CoalHeritage** addresses the cultural significance of industrial legacies. Additionally, the **USAMIN** project contributes to international knowledge transfer by the creation of an international online Moodle course titled *Use of Abandoned Mines*. Current projects, **REMINDNET**, **CRMsDataSpace**, and **RAISING**, focus on networking about the legislation, governance and management of mining legacies, improving data management for critical raw materials in closed extractive coal waste facilities, and promoting public participation in the transition process, respectively. In this paper, these projects are described in detail to provide scalable tools for achieving resilient land-use transformation in mining regions worldwide.

Keywords: Post-mining transformation, Industrial heritage, Just transition

1. Introduction

Industrial underground mining of hard coal in Germany began in the early 19th century, primarily in the Ruhr and Saar Regions, where Germany's largest hard coal deposits are located. For decades, the industry was a cornerstone of the German economy with several hundred mining companies of various sizes. However, the rise of oil and cheap global imports in coal and steel triggered the collapse of the Ruhr's core sectors. In 1968, the remaining mining companies in the Ruhr Region merged their coal activities under the supervision of the Ruhrkohle AG, later restructured into RAG Aktiengesellschaft (RAG AG) in 1997, in order to establish a stable economic and social basis for the industry and its workforce. In 2007, the Federal Government, the states of North Rhine-Westphalia and Saarland, the RAG Corporation, and the mining union IGBCE agreed to terminate hard coal subsidies by the end of 2018. Based on this agreement, the RAG Foundation was established in June 2007 to manage mine closures and finance the perpetual obligations including mine water management, polder measures, and groundwater purification (Zeqiri et al., 2024; RAG Stiftung, 2026).

The closure of hard coal mines in Germany has taken place for decades, bringing a wide range of tasks that have to be fulfilled. To meet these challenges, the graduate program “Geotechnical Engineering and Post-Mining” was established at the University of Applied Sciences Georg Agricola (THGA) in 2013. This was followed by the founding of the Research Center of Post-Mining (FZN) in 2015, which is the only institution of its kind worldwide. The center is carrying out its research across four strategic pillars as given in Figure 1. The first pillar, Perpetual Tasks and Mine Water Management, focuses on a comprehensive understanding of hydrological systems to develop near-nature solutions for water resources in former mining regions. The

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second pillar, Geomonitoring in Post-mining, integrates diverse geoinformation into detailed 3D models to simulate post-mining processes and establish viable risk management systems. In the third pillar, Material Sciences for the Preservation of Industrial Heritage, researchers focus on the conservation of abandoned collieries and equipment by analyzing environmental impacts on materials and developing new investigation techniques. Finally, the fourth pillar, Land Use & Transition, involves a detailed analysis of the political, economic, and legal frameworks required to successfully repurpose former industrial locations. By evaluating these transition requirements, the pillar creates the necessary foundations for transforming former mining sites into new residential districts, business parks, recreational areas, or facilities for renewable energy. (FZN, 2026).

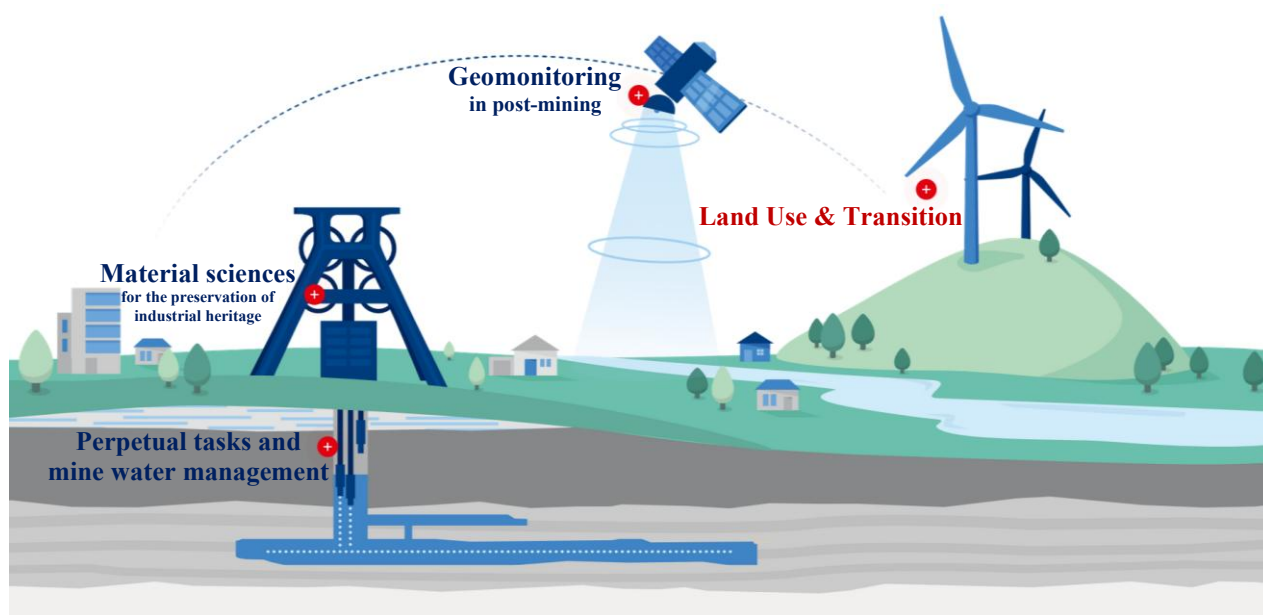


Figure 1: Strategic pillars of the Research Center of Post-mining

In addition, the integration of geospatial information, environmental monitoring data, and digital platforms increasingly supports evidence-based decision-making for post-mining land use planning and regional transformation.

2. Land Use & Transition

Land Use & Transition focuses on the detailed analysis of the political, economic, and legal frameworks required to successfully repurpose former industrial locations. In recent years, these governance approaches have increasingly been complemented by data-driven tools, including geospatial analysis, environmental monitoring, and digital platforms that support strategic planning in post-mining landscapes. By evaluating these transition requirements, considering regional objectives and public involvement, this pillar creates the necessary foundations for transforming former mining sites into lively new residential districts, modern business parks, recreational areas, or specialized facilities for renewable energy. An overview of the ongoing and completed projects within this department are given detailed below.

2.1. Ongoing Projects

Building on our established expertise, our ongoing projects aim to provide scalable tools and frameworks that ensure a resilient and data-driven land-use transformation in mining regions worldwide.

RAISING (Raising Awareness and Improving Social Engagement for the Just Transition of Mining Regions): The project focuses on increasing public awareness, particularly within small local communities, regarding the necessary transformation of hard coal and lignite mining regions, and the promotion of new strategies for regional development. The project is built on three main pillars:

- Identification of the main premises determining the process of transformation of hard coal and lignite mining industry: Providing policymakers and the public with open access to user-friendly socio-economic and environmental data, alongside information on global decarbonization trends.
- Strengthening public participation: Engaging stakeholders through dedicated support tools, including workshops, webinars, public debates, and an interactive catalogue of "good practices" for innovative regional solutions.
- Implementation of an educational and social campaigns: Supporting the development of the regional potential through targeted communication activities and media campaigns to highlight the sustainable development opportunities of post-mining areas.

The implementation of the project is organized into Work Packages (WPs) with the following operational objectives:

- WP1: Coordination, dissemination and promotion
- WP2: Identification of the main premises determining the process of coal transformation
- WP3: Developing the potential of mining regions into sustainable development centres - Education and social campaign
- WP4: Development of partnership network and engaging of small community stakeholders

This 24-month project is funded by the EU Research Fund for Coal and Steel (RFCS). It started September 1, 2025 and will run until August 31, 2027. Project consortium includes the Central Mining Institute (GIG-PIB) and Instrat from Poland, the Technical University of Ostrava (VSB) from the Czech Republic, and University of Applied Sciences Georg Agricola (THGA) from Germany (RAISING, 2026).

CRMsDataSpace (Common European Data Space on Critical Raw Materials for the Green Deal: Recovery Potential from Closed Extractive Coal Waste Facilities): This project aims to develop a Common European Data Space on Critical Raw Materials (CRMs) for the Green Deal, with a strong focus on recovering valuable raw materials from closed extractive coal waste facilities. The project is built on the following core pillars:

- Creation of a European Digital Data Platform: Developing a centralized geospatial database to identify, assess, and map critical raw materials within extractive waste facilities.
- Use of Artificial Intelligence (AI) and Large Language Model: Utilizing Artificial Intelligence (AI) and Large Language Models (LLMs) to automate data processing, classification, and reporting, thereby enhancing the efficiency of CRM recovery projects.
- Technical and Economic Validation: Conducting geochemical and metallurgical assessments to determine resource viability in coal waste, while developing sustainable business models to attract industrial investment.
- Knowledge Transfer and Capacity Building: Organizing workshops, training sessions, and dissemination events to ensure broad adoption and collaboration across EU Member States.

These objectives are carried out within the scope of seven Work Packages:

- WP1: Project coordination and management
- WP2: Data acquisition from closed facilities
- WP3: Development of the data catalogue
- WP4: Deploying a minimum viable data space
- WP5: Multi-side business solutions
- WP6: Artificial intelligence (AI) tools
- WP7: Communication and dissemination

This 36-month project is funded by the Research Fund for Coal and Steel (RFCS). It began on July 1, 2025, and will conclude on June 30, 2028. The consortium combines expertise in mining engineering, geosciences, and AI, collaborating with three universities and five industrial partners from Poland, Spain, Belgium, Romania, and Germany (CRMsDataSpace, 2026).

REMINDNET (Recovery of Mining District Network): This project establishes a European network of over 130 scientists and engineers from more than 60 organizations across 37 countries, aimed at addressing the complex legacies of mineral and metal extraction. The network focuses on the legislation, governance and management of mine legacies, as well as financing, rehabilitation and monitoring techniques, with the goal of improving implementation to minimize post-closure mining legacies. The project is built on two primary pillars:

- Research Coordination: Developing a common understanding of sustainable mine legacy management, comparing current legal frameworks and governance structures, establishing a European

mining legacy database with QGIS visualisation, and providing input to mine authorities, regulators and financial institutions via an open access platform

- Capacity Building: Establishing and maintaining a "Community of Practice", pooling experts from currently separated field and involving specific target groups such as Early Career Investigators, under-represented genders, and experts from countries with limited existing capacity in mine closure management.

To achieve these objectives, the project is structured into 5 Working Groups (WGs) as follows:

- WG1: Government and management practices
- WG2: Socio-economic aspects and financing
- WG3: Environmental monitoring and risk management and use of abandoned mine
- WG4: Training and capacity building
- WG5: Dissemination and communication, Project Management

REMINDNET is a COST Action, a research network funded by the European Cooperation in Science and Technology (COST). The action began on October 19, 2023 and will be completed on October 18, 2027 (REMINDNET, 2026).

The overview of ongoing projects in the department of Land Use & Transformation is provided in Table 1.

Table 1: Ongoing research projects in the department of Land Use & Transition

Project name	Funding	Duration	Key focus	Involved countries
RAISING	RFCS	2 years	Public awareness, social engagement, and just transition	PL, CZ, DE
CRMsDataSpace	RFCS	3 years	AI-driven data space for critical raw material recovery from coal waste	ES, PL, RO, BE, DE
REMINDNET	COST	4 years	Legislation, governance and management of mining legacies	37 countries (mainly EU)

2.2. Completed Projects

The successfully completed projects funded by various European initiatives have provided the strategic business models and cultural frameworks necessary for resilient post-mining transitions.

GREENJOBS (Leveraging the competitive advantages of end-of-life underground coal mines to maximize the creation of green and quality jobs): This RFCS-funded project (2022-2025) focused on identifying and promoting new green business opportunities within coal regions in transition. By analyzing former coal mining infrastructures, the project integrated technical deployment with training and reskilling of workers, rather than treating technology and employment as separate issue. The project was structured across four strategic strands (GreenJOBS, 2026):

- Renewable Energy & Storage Deployment: Mapping the feasibility and grid integration of diverse technologies suited for post-mining environments, including geothermal energy from mine water, solar photovoltaic, wind power, unconventional pumped hydro, battery storage and green hydrogen.
- Circular Economy & Restoration: Developing solutions such as soil substitutes for land restoration, dense fluids for pumped hydro, and the recovery of critical raw materials (CRMs) to reduce remediation costs and create new revenue streams.
- Place-Based Transition Visions: Exploring renewable-powered futures for specific mining complexes in Poland, Spain and Slovenia through detailed case studies to match local assets, constraints, workforce characteristic and community priorities.
- Integrated Workforce Planning: Identifying and categorizing key occupations, mapping and assessment of those occupations, designing training and re-skilling programs to help public authorities, employers, social partners and training providers move from broad ambitions to actionable workforce plans.

CoalHeritage (Conservation and promotion of the Coal Mining Heritage as Europe's cultural legacy): Funded by the RFCS, this project (2023-2025) addresses the preservation of industrial culture across Greece, Poland, France, Slovenia, and Germany. It focuses on the development of an interregional network for the promotion and protection of coal mining heritage in mining regions. The project's impact is categorized into four key areas (CoalHeritage, 2026):

- **Industrial & Economic Growth:** Identifying best practices for transforming mining sites into museums and cultural objects. These "after-use" concepts encourage private investment and create new service-sector jobs, such as tourism and education, to counteract the loss of traditional mining employment.
- **Social & Environmental Responsibility:** Promoting regional identity and a "sense of belonging" by declaring former mines as national heritage sites. This process includes reskilling former workers for heritage management and improving the environmental quality of industrial spaces through adaptive reuse.
- **Digital Preservation & Mapping:** Developing a web-based European Visual Map Journal (EVMJ). This tool documents the assets of selected mines and is designed for integration into the European Route of Industrial Heritage (ERIH).
- **Scientific Outcomes:** Systematizing knowledge about coal mines, mining processes and related technologies while providing an open access area for knowledge exchange. This serves to promote and increase stakeholder awareness of industrial heritage while building an interregional network to foster collaboration.

WINTER (Web INTERactive management tool for coal Regions in transition): Within the scope of the RFCS-funded project (2021–2024), an interactive digital platform to support the management of coal regions undergoing structural change was developed. By analyzing three pilot regions, the Ruhr Region in Germany, West Macedonia in Greece, and Konin in Poland, at different stages of transition, the project created a framework for optimizing transition strategies. The project's impact is defined by three main pillars (WINTER, 2026):

- **Interactive Management Tools:** Development of a web-based platform for addressing environmental and socioeconomic challenges that utilizes interactive maps and multimedia content to document the rehabilitation and reclamation progress of former mining sites. The tool provides local municipalities, policymakers, and social partners with concrete recommendations for practical implementation based on "best and worst practice" examples while allowing for the comparison of transition scenarios and the transfer of findings to other coal regions across Europe.
- **Governance and Socio-Economic Analysis:** Identifying and surveying technical, legal, and socioeconomic structures within the pilot regions and development of the "Transition Management Handbook" with lessons learnt, recommendations for governance, institutional structures and implementation, as well as community participation.
- **Stakeholder Engagement:** Facilitating knowledge exchange through workshops and final progress meetings with industry and government representatives, ensuring that the project's digital tools align with the needs of those managing the transition on the ground.

POTENTIALS (Synergistic potentials of end-of-life coal mines and coal-fired power plants, along with closely related neighbouring industries): This RFCS-funded project carried out from 2021 to 2023 focused on the unique aspects of coupled end-of-life coal mine sites, coal-fired power plants, and closely related neighbouring industries, using their synergistic opportunities to stimulate new economic activities and jobs in Coal Regions in Transition, guaranteeing a sustainable and combined use of assets and resources otherwise overlooked in the high-velocity environments of phasing out processes. The project's impact is defined by three core pillars (POTENTIALS, 2026):

- **Prospective Scenario Analysis:** Utilizing strategic foresight to identify business models focused on renewable energy, energy storage, and the circular economy. This ensures that assets and resources, which are often overlooked during the rapid phase-out process, are utilized for sound decision-making.
- **Territorial Just Transition Support:** Providing a practical evidence base for updating Territorial Just Transition Plans (TJTPs). This helps Member States align regional strategies with the European Green Deal, ensuring a fair transition that leaves no one behind.
- **Economic Diversification and Synergies:** Delivering feasible reuse options for coupled end-of-life coal assets and related infrastructure. By allowing neighboring industries to "green" their power purchases, the project fosters long-term economic growth and regional resilience.

USAMIN (Use of Abandoned Mines): Funded by the EU's Erasmus+ program (2021-2023), USAMIN was based on the shared knowledge, experience and best practices regarding the challenges and opportunities of the post-mining era from project partners in Germany, Spain, Poland, and the Czech Republic. The project's impact is defined by three key pillars (USAMIN, 2026):

- **Intellectual Output:** Development of a comprehensive international Moodle course titled "Use of Abandoned Mines." This digital platform provides individual teaching materials designed to equip

stakeholders in transition regions with technical and strategic know-how on topics such as methane emissions, reclamation, and geothermal reuse.

- Training: A highlight of the project was the Summer School held in July 2022 in Ostrava, Czech Republic. This event brought together more than 30 students and 10 teachers from around the world. The in-person collaboration and student feedback were instrumental in refining the course content and ensuring its global relevance.
- Capacity Building and Networking: USAMIN connected actors from regions at the beginning of their transition with established experts. The project fostered long-term cooperation and culminated in the specialist conference, "The Potential of Abandoned Mine Workings in the EU," establishing a lasting network for sustainable post-mining strategies.

Table 2 summarizes the foundational projects that have successfully concluded, providing the strategic, cultural, and educational frameworks currently utilized in European coal regions in transition.

Table 2: Completed research projects in the department of Land Use & Transition

Project name	Funding	Focus Area	Key focus
GreenJOBS	RFCS	Renewable energy, economic transitions	Repurposing coal mines for renewable energy and circular economy technologies to maximize high-quality green job creation.
CoalHeritage	RFCS	Cultural heritage, regional networks	Enhanced regional management to develop jobs in new sectors and the design of the European Visual Map Journal (EVMJ)
WINTER	RFCS	Social acceptance, participation, governance, fair transition	Development of an EU-wide web platform and comparative case studies to optimize transition management
POTENTIALS	RFCS	Business models, industrial synergy	Systematic evaluation of coupled coal mines and power plants to stimulate new economic activities and jobs in transition regions.
USAMIN	Erasmus+	Education, knowledge transfer	International Moodle course on the subject of Use of Anadoned Mines

3. Conclusion

The research portfolio within the Land Use & Transition pillar represents a comprehensive response to the structural transformation associated with the European coal phase-out. By combining governance frameworks with technological innovation, geospatial data infrastructures, and stakeholder engagement processes, the department contributes to more resilient and evidence-based pathways for the transition of former mining regions.

Through the transformation of former mining sites into diverse assets, ranging from museums and cultural heritage locations to residential districts and innovative business parks, the department supports the preservation of industrial identity while enabling new regional development opportunities. Projects such as CoalHeritage and USAMIN highlight the cultural and educational value of mining legacies, while initiatives like GreenJOBS and POTENTIALS promote the transition toward renewable energy systems and circular economy solutions by identifying synergistic business models for post-mining infrastructures

Through the CRMDataSpace project, the recovery of critical raw materials from closed extractive coal waste facilities is focused, while within the scope of the RAISING and WINTER projects, the department provides a scalable methodology for successful regional transformations that balances economic diversification land restoration, and social stability. Finally, the activities of the REMINDNET research network, focusing on the legislation, governance and management of mine legacies, as well as financing, rehabilitation and monitoring techniques, contribute to addressing the complex challenges raised by post-mining.

Acknowledgments

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RAISING: A Participatory Framework for Just Transition in Small European Coal Communities

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Abstract

Coal regions across Europe face accelerated structural change driven by decarbonization policies and mine closures. While regional and national transition strategies have received considerable attention, small and medium-sized municipalities directly affected by mining phase-out have received comparatively less focus. These communities often face demographic decline, economic dependency, environmental legacies, yet are critical for socially legitimate transition pathways. The European project RAISING addresses this gap through a participatory framework tailored to small coal communities in Germany, the Czech Republic, and Poland. This contribution outlines the project's conceptual foundations, territorial selection methodology, and initial implementation roadmap. Using a multi-criteria framework of demographic, geographic-administrative, and socio-economic indicators, priority regions and focal municipalities were identified to ensure vulnerability relevance and engagement potential. RAISING conceptualizes participation as a governance instrument rather than a communication tool, aiming to strengthen transparency, stakeholder coordination, and local ownership of transformation processes. The project's phased implementation strategy integrates baseline assessments, stakeholder mapping, co-creation formats, and cross-country knowledge exchange. By demonstrating how participatory governance can be systematically operationalised at the municipal scale, this paper contributes to the debate on just transition implementation and positions small coal communities as strategic actors in post-mining transformation across Central Europe.

Keywords: Just transition, Post-mining regions, Public participation, Best practices, Coal regions in transition

1. Introduction

Across Europe, coal regions are undergoing a profound restructuring necessitated by decarbonization policies, environmental imperatives, and the transformation to sustainable and renewable energy (European Commission, 2020). While regional and national transition strategies have received significant policy attention, the transformation processes unfold most visibly at the local level, particularly in small and medium-sized communities directly affected by mine closures and transition. These groups frequently face demographic decline, economic dependency on mining-related employment, environmental legacies, and limited administrative capacity.

The European project RAISING responds to this gap by placing small coal communities at the centre of participatory transition governance. Rather than concentrating on macro-regional planning instruments alone, the project aims to strengthen participatory governance, societal engagement, and awareness-building at the municipal scale. The central premise of RAISING is that a just transition requires not only economic diversification and environmental remediation, but also inclusive and well-designed participatory processes that enhance local ownership and social legitimacy (RAISING, 2026).

This contribution presents the conceptual framework, territorial selection methodology, and implementation roadmap established during the project's initial phase. As the project has recently started, the

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discussion focuses on the structured approach adopted to identify priority regions and communities, while outlining the operationalization of participatory mechanisms across diverse governance contexts.

2. Conceptual Framework: Participation as a Governance Instrument

The concept of just transition extends beyond economic compensation or employment substitution. It encompasses procedural justice, distributional fairness, social inclusion, and long-term territorial resilience. In coal regions, transition processes are often characterized by uncertainty, contested narratives, and identity shifts linked to the historical role of mining (Frankfurt School of Finance & Management, 2023).

The RAISING project approaches participation not as a simple communication exercise, but as a meaningful part of governance itself. In coal communities facing closure and restructuring, participation can help ease tensions, build trust between institutions and citizens, improve coordination among local actors, and give residents a real voice in shaping their future.

Small communities are a particularly important scale for this work. They are often the first to feel the social and economic consequences of mine closure, yet they typically have fewer administrative and financial resources than larger cities. At the same time, these municipalities often benefit from strong social ties, active local networks, and committed civic initiatives. When supported through well-designed participatory processes, these existing relationships can become a powerful foundation for collaborative vision-building and locally grounded transition pathways.

The project therefore integrates participatory planning approaches with multi-level governance perspectives, thereby connecting local agency with broader European decarbonisation strategies (European Commission, 2019).

3. Identification of Priority Regions and Small Communities

3.1. Selection Guideline

The project employs a structured and transparent methodology to identify priority regions and communities in the three participating countries. The selection process is based on a multi-criteria framework that combines demographic, geographic-administrative, and socio-economic indicators as shown in Table 1.

Table 1: Selection criteria for identifying priority small coal communities within the RAISING project

Category	Sub-criteria	Condition
Demographic	Population size	Typically, < 50,000 residents
	Population trends	Declining or stagnant population, indicating challenges in maintaining local economy and services
Geographic & Administrative	Location	Within or adjacent to mining regions (hard coal or lignite)
	Administrative scope	Includes towns, villages, or municipal districts directly affected by mine closure or downsizing
Socio-economic & Transition Indicators	Economic dependency	Local economy dependent on mining employment (notably high share of workforce in mining or related sectors)
	Transition vulnerability	High vulnerability to restructuring due to low industrial diversification or high unemployment
	Environmental & infrastructure issues	Mining-related challenges such as subsidence, mine waste, or water contamination
	Community readiness / engagement	Presence of local organizations, citizen initiatives, or demonstrated willingness to participate in transition processes

The selection criteria combined demographic, geographic, and socio-economic dimensions. From a demographic perspective, the focus was placed on municipalities typically below 50,000 inhabitants experiencing declining or stagnant population trends. Geographically and administratively, attention was given to towns and districts located within or adjacent to hard coal or lignite regions directly affected by mine closure or downsizing processes. Furthermore, socio-economic and transition-related indicators were considered, including a strong dependency on mining employment, vulnerability to economic restructuring, the presence of environmental and infrastructural legacies, and evidence of community readiness or willingness to engage in transition processes. This structured and multi-dimensional framework ensures that the selected communities reflect both high levels of structural vulnerability and a meaningful potential for participatory engagement.

3.2. Priority Regions

RAISING focuses on three coal regions in transition: the Ruhr Region in Germany, the Northern Bohemia and Moravian-Silesian Regions in the Czech Republic, and the Silesian Voivodeship Region in Poland. These territories have been deeply shaped by hard coal and lignite mining and continue to experience significant socio-economic and environmental challenges linked to coal phase-out processes.

The Ruhr Region represents one of Europe's most prominent examples of long-term structural transformation following the decline of hard coal mining, offering important lessons on governance, regional diversification, and post-mining management (Oei et al., 2020). The Northern Bohemia and Moravian-Silesian areas are characterized by ongoing restructuring pressures, environmental legacies, and policy adjustments in the context of lignite and hard coal transition (Lyons, 2023). The Silesian Voivodeship Region in Poland remains strongly connected to coal-based activities and is currently navigating complex socio-economic adjustments within the broader framework of European decarbonization and national transition strategies (Mazur and Ogrodniczuk, 2023). Particular attention is also given to cross-border mining area Turów lignite mine, located at the intersection of Poland, the Czech Republic, and Germany, where mining activities and future closure processes have raised environmental and governance discussions across national boundaries.

Within each region, specific small and medium-sized municipalities were selected as focal communities for project activities. Spatial characterization and GIS-based mapping support territorial comparability and provide a clear visual understanding of demographic, economic, and structural conditions as shown in Figure 1. The figure map composition highlights transition areas and focal communities rather than strictly delineating national administrative boundaries, which explains the inclusion of cross-border mining contexts such as the Turów area. By operating across regions with diverse governance systems, mining legacies, and transition dynamics, RAISING establishes a robust framework that provides scalability and transferability of its participatory models.

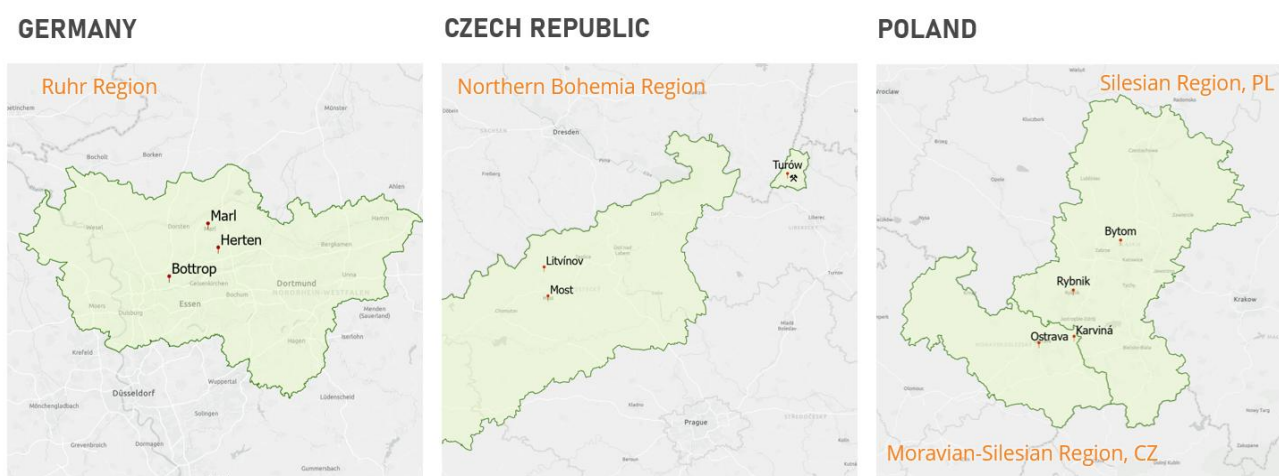


Figure 1: Spatial distribution of the three priority regions selected within RAISING: Ruhr Region (Germany), Northern Bohemia and Moravian-Silesian Region (Czech Republic), and Silesian Region (Poland)

4. Implementation Roadmap

As RAISING is currently in its initial phase, the project places strong emphasis on structured process design and methodological clarity. The implementation strategy is organized into four interconnected stages that translate the project's operational objectives into concrete actions at the level of small coal communities.

Figure 2 illustrates this step-by-step roadmap, showing the progression from baseline assessment and stakeholder mapping to participatory engagement, capacity building, and finally, synthesis and policy integration. The staged structure reflects the project's intention to move from evidence-based analysis to locally embedded engagement, ultimately, to transferable governance recommendations.

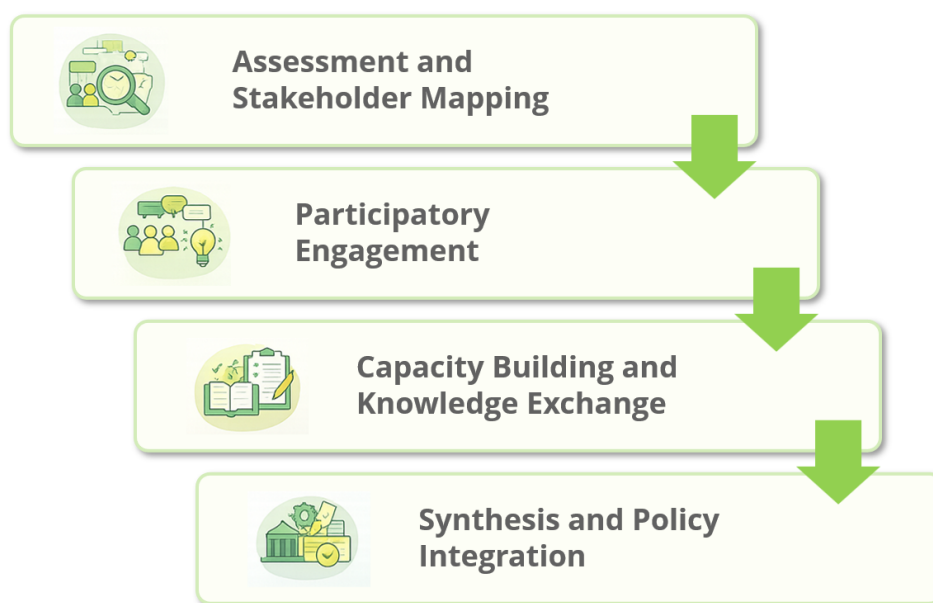


Figure 2: Conceptual implementation roadmap of the RAISING project.

4.1. Baseline Assessment and Stakeholder Mapping

The first stage focuses on establishing a solid analytical foundation. In line with Objective 1, this phase involves identifying the main premises shaping coal transition processes and compiling relevant socio-economic and environmental data. Particular attention is given to making information accessible and understandable for both local communities and decision-makers. At the local level, the project analyses governance structures, identifies key stakeholders, and assesses community readiness. Stakeholders include:

- municipal authorities and regional decision-makers,
- civil society organizations, citizen initiatives,
- educational institutions and research centres
- trade unions, and local businesses.

The goal of this stage is to build a shared understanding of transition challenges, structural vulnerabilities, and existing capacities before launching participatory activities.

4.2. Participatory Engagement

Building on the baseline assessment, the second stage operationalises Objective 2 by strengthening public participation in small coal communities. Rather than applying a uniform engagement model, RAISING adapts formats to local institutional cultures and socio-economic contexts. Planned activities include

- stakeholder workshops,
- public debates, webinars, and
- multi-actor dialogue platforms.

These formats aim to engage vulnerable groups, disseminate knowledge, and facilitate discussions about the future of mining regions. This phase will have as an outcome the development of an electronic catalogue

and interactive database of good practices, enabling communities to access examples of participatory approaches and sustainable transition solutions.

4.3. Capacity Building and Knowledge Exchange

To ensure long-term impact beyond the project duration, RAISING integrates targeted capacity-building measures, in line with Objective 3. This stage focuses on the development of educational and social campaigns tailored to the specific realities of small mining communities. The project promotes cross-country exchange between Germany, the Czech Republic, and Poland, enabling mutual learning and comparative reflection on governance and participation models. Guidance materials and practical recommendations will support municipalities in strengthening their role in transition processes.

4.4. Synthesis and Policy Integration

In the final stage, the insights generated through data analysis, participatory engagement, and capacity-building activities will be synthesized into a structured participatory framework. The aim is to translate local experiences into actionable recommendations for policymakers and practitioners. Particular attention will be given to alignment with national transition strategies and EU-level mechanisms, including Just Transition funding instruments. By connecting local engagement processes with broader policy frameworks, RAISING seeks to enhance both the legitimacy and effectiveness of coal region transformation pathways.

5. Expected Contributions

Although empirical results are still forthcoming, RAISING is strategically designed to contribute in three closely interrelated dimensions.

1. **Governance innovation:** The project advances governance innovation by operationalising participation as a structured governance approach, particularly suited to small municipalities with limited administrative capacity.
2. **Social resilience:** By fostering inclusive dialogue and raising awareness, the project aims to strengthen social resilience. This enhances local ownership of transition processes and reducing uncertainty and resistance associated with mine closures.
3. **European added value and transferability:** Through its multi-country design and clearly defined selection methodology, RAISING seeks to develop a replicable and transferable model that can be adapted to other coal regions in transition across Europe.

6. Conclusions

The transformation of coal regions represents one of the most significant socio-economic restructuring processes in contemporary Europe. While macro-level policy frameworks are essential, the success of just transition ultimately depends on local governance quality and societal engagement.

RAISING responds to this challenge by focusing on small coal communities and developing a structured participatory framework grounded in transparent selection criteria, territorial analysis, and tailored engagement formats. By outlining the conceptual design and implementation roadmap at its early stage, this contribution demonstrates how participatory governance can be systematically embedded in post-mining transition strategies, strengthening both social legitimacy and policy effectiveness in coal regions across Europe.

Acknowledgments

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Mining Heritage Management in the Portuguese Sector of the Iberian Pyrite Belt: Insights from the Post-Mining Towns of Lousal and São Domingos

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Abstract

Mining landscapes in the Portuguese sector of the Iberian Pyrite Belt (IPB) embody a layered legacy of industrial exploitation, environmental degradation, and socio-economic disruption. Since the closure of most large-scale operations in the late twentieth century, different actors have advanced diverse strategies to rehabilitate and valorise former mining territories to benefit from cultural tourism economy. This paper examines two emblematic post-mining towns – Lousal and São Domingos – to analyse how remediation, musealisation, and tourism development have been articulated in practice. The study draws on a review of academic and institutional literature, site visits conducted in October 2025, and semi-structured interviews with site managers and staff. It documents current site conditions, institutional arrangements, and planned initiatives, and examines heritage management models and their socio-economic implications. Findings indicate two distinct post-mining scenarios: Lousal represents a structured rehabilitation model combining environmental remediation, scientific education, and heritage tourism, while São Domingos reflects a more landscape-oriented and urban-centred approach, where selective building restoration coexists with evocative industrial ruins within a post-mining landscape. These cases highlight both the opportunities and constraints of mining heritage management in regions shaped by extractive legacies.

Keywords: Post-mining, Rehabilitation, Mining heritage, Heritage management, Museum, Tourism

1. Introduction

The Iberian Pyrite Belt (IPB) is one of the world's most significant volcanogenic massive sulphide provinces, extending from southern Portugal into the Spanish regions of Andalusia (Matos & Martins, 2006; Tinoco et al., 2002) (See Figure 1). Geologically rich in copper, zinc, lead, and sulphur deposits, the IPB has sustained mining activity since Antiquity, with renewed expansion during the late nineteenth and early twentieth centuries both foreign and national mining companies. In Spain the belt notably includes the mines of Riotinto and Tharsis. In Portugal, it stretches across the Alentejo, where mines such as Caveira, Lousal, Aljustrel, Neves Corvo, and São Domingos became central to regional economic life and international mineral markets, responding to global demand for pyrite and copper concentrates (Matos & Martins, 2006). These operations profoundly transformed local landscapes and communities, generating employment and providing infrastructure and facilities. Entire towns were created from scratch around mining sites, cultivating strong mining identities spanning regions with shared histories and cultures (Fonseca, 2007; Oliveira, 2015). Simultaneously, mining is associated with harsh work conditions and, in many cases, worker exploitation (Silva, 2012). In addition, mining activity has produced severe environmental degradation and pollution, affecting both ecosystems and the health of miners and their families (Fidalgo 2018; Guimarães, 2022). In São Domingos, for instance, the Achada do Gamo furnaces, used for sulphur roasting, emitted fumes containing sulphur dioxide, which caused severe air pollution and damaged surrounding agricultural land. This reality provoked one of the earliest recorded environmental protests in Portugal, ultimately leading to the total abandonment of the roasting technique (Silva, 2012; Peyton, 2017).



Figure 1: Location of Key Mining Sites in the Iberian Pyrite Belt (Portugal and Spain). Map produced by the author using Google Earth Pro.

By the late twentieth century, the closure of most mines in the Portuguese IPB left behind complex post-mining realities. Economically, local communities faced unemployment and depopulation. Environmentally, abandoned infrastructures and tailings posed long-term risks (Matos & Martins, 2006). In 2001, The state assumed responsibility for the environmental rehabilitation of degraded mining areas to be led by EDM – *Empresa de Desenvolvimento Mineiro* (Decree-Law No. 198-A/2001). In the context of rehabilitation, mining heritage has emerged as a strategic framework (EDM & DGEG, 2011). Local authorities, foundations, and national institutions have applied different models of valorisation and communication of mining heritage, positioning mining tourism as a driver for local development (Craveiro et al., 2013).

A review of these interventions demonstrates that most took place between the 1990s and the 2000s. The literature lacks updated accounts of the current status and an overall assessment of these interventions. In this paper, we examine two post-mining towns in the Portuguese IPB – Lousal and São Domingos – aiming at: (1) documenting current post-mining realities, site conditions, institutional arrangements, and planned initiatives; (2) investigating how former mining sites are being valorised and repurposed; and (3) examining heritage management models and their socio-economic outcomes. Doing so, the paper contributes to ongoing debates on post-mining transitions, highlighting how institutional configurations, remediation strategies, and interpretive choices shape divergent pathways of heritage management within the same geological region.

Lousal is a former pyrite mining village in the Municipality of Grândola in southern Portugal. Modern industrial extraction began in 1900. In 1937, ownership passed to SAPEC (*Sociedade Agro-Pecuária e Comercial*), which exploited pyrite deposits for sulphuric acid and fertiliser production, providing employment for approximately 1,100 workers at the peak of mining activity (Rodrigues, 2005). Lousal witnessed drastic development, with housing, medical services, education, and commercial facilities structured around the mine's activity. However, declining profitability and broader restructuring of the mining sector led to the mine's closure in 1988, generating socio-economic disruption, unemployment, and demographic decline, and leaving behind degraded landscapes (Rodrigues, 2005). Following closure, the RELOUSAL project (Revitalisation, Renewal, Recovery and Rehabilitation of Community Life in Lousal), launched in 1994, implemented an integrated redevelopment strategy combining heritage preservation, science communication, environmental rehabilitation, and tourism (Oliveira et al., 2013; Relvas et al., 2014). Institutionalised through a partnership between the former mine owner SAPEC and the Municipality of Grândola, and supported by the creation of the Frédéric Velge Foundation, the initiative led to substantial urban rehabilitation and the establishment of the Lousal Cultural Complex, comprising the Mining Museum,

the Centro Ciência Viva do Lousal and an outdoor interpretive route across remediation areas with access to part of the underground workings.

São Domingos is a former pyrite mining village in the Municipality of Mértola in southern Portugal. The site's modern industrial history began in the mid-nineteenth century. After the rediscovery of pyrite deposits in 1854, the French industrial company *La Sabina* took ownership and leased it to the British mining company Mason & Barry Ltd in 1858, which built the town and associated infrastructure. These included one of the first railways in the country, of 17km, connecting the mine to Pomarão's riverport to export extracted materials mainly to England, contributing to its industrial development as vital inputs for Swansea's smelters, British explosives, and wartime petrochemicals (Peyton, 2017; Silva, 2010). São Domingos also had the first power station and the first silent film cinema in the Alentejo region, among many other facilities uncommon to find in neighbouring towns (Dias-Sardinha et al., 2010; Silva, 2010). The mine reached a peak workforce of approximately 2,400 workers (Alves, 1997). Meanwhile, labour exploitation, miners' strikes, social segregation and severe environmental impacts were characteristic of its mining history (Alves, 1997; Silva, 2012). Mason & Barry went bankrupt in 1966, leading to an abrupt mine closure. The mining site was looted of equipment and material and was abandoned to vandalism and decay. Environmental damage due to mining was deemed one of the highest in the country (Matos, Soares & Cardoso, 2006) with a dramatically altered post-mining landscape. In 2013, the entire São Domingos mining complex was classified as an Ensemble of Public Interest (Ordinance 414/2013), acknowledging the significance of its industrial and mining heritage. Town rehabilitation has since been led primarily by the Municipality of Mértola, in coordination with the landowner, *La Sabina*, both establishing the *Serrão Martins Foundation* in 2004 to safeguard and promote the mining heritage of the town. The Foundation plays a central role in cultural management, in charge of documentation, archiving, collection of oral histories, overseeing the operation of the *Cinetatro* and the reconstructed miner's dwelling (*Casa do Mineiro*), organising exhibitions and educational initiatives, and providing guided visits across the site.

2. Materials and Methods

This study adopts a qualitative case study approach combining documentary analysis and fieldwork. The literature review addressed mining heritage activation in Portugal more broadly – forming the basis of a separate publication – as well as the historical trajectory and institutional development of heritage initiatives at Lousal and São Domingos. This provided the analytical framework for interpreting the empirical material. Lousal and São Domingos were selected because their mining activity has definitively ceased – unlike Aljustrel and Neves Corvo – allowing for the assessment of both post-mining trajectories and processes of heritagisation and musealisation. The two cases differ in scale, remediation strategies, institutional arrangements, levels of musealisation, tourism development, and the treatment of social history. These contrasts, alongside shared characteristics such as environmental legacies, socio-economic restructuring, and the presence of art- and community-based initiatives, allow for a complementary reading of distinct post-mining pathways.

Fieldwork was conducted in October 2025 at Lousal (21–24 October) and São Domingos (27–31 October). It included unguided and guided site visits, systematic observation of industrial remains and exhibition spaces, photographic documentation, and informal conversations with staff and local actors. Particular attention was paid to spatial organisation, interpretive strategies and narratives, remediation areas, accessibility, visitor infrastructure, and the physical condition of the site and built structures. At Lousal, the visit was conducted with science communicator Margarida Oliveira and included access to permanent exhibitions, outdoor remediation zones, and interpretive routes. At São Domingos, fieldwork was carried out with Manuel Marques (Municipality of Mértola) and *Fundação Serrão Martins* staff members, and included observation of the mining complex, restored public buildings, miners' housing, and cultural venues. Attendance at a public participatory workshop organised within the framework of the INCOME project¹ (University of Évora) provided additional insight into environmental concerns, community perspectives, and current research partnerships.

Semi-structured interviews were conducted online following the visits with site directors and senior officials responsible for heritage management and programming, including Álvaro Pinto (ACCVL director in Lousal) and Manuel Marques (senior municipal official, Municipality of Mértola). Interviews explored

¹ <https://www.income.uevora.pt/>

institutional arrangements, funding structures, remediation processes, exhibition narratives, tourism dynamics, community participation, and future plans. Both interviews were conducted with informed consent and audio-recorded for transcription. Following data collection, the case studies were analysed thematically around five analytical dimensions (Table 1): (1) post-mining realities and management; (2) heritage interpretation and communication; (3) tourism and socio-economic impacts; (4) art and community initiatives; and (5) planned initiatives and future directions. The objective is not a strict comparison but a complementary examination of two distinct post-mining trajectories, illuminating broader debates on mining heritage management in Portugal.

3. Results and Discussion

Table 1: Post-Mining Management Models in Lousal and São Domingos

Dimension	Lousal	São Domingos	
1. Post-Mining Realities & Management	<i>Environment & Remediation</i>	Managed contamination, structured remediation	Severe but managed contamination, partial remediation
	<i>Governance</i>	Hybrid public–private governance, former mining company remains involved	Hybrid public–private governance, municipally sustained, limited landowner engagement
2. Heritage Interpretation & Communication	<i>Offer</i>	Managed and ticketed infrastructure, including a museum, a science centre, and a mine gallery section; free-access mining site	Managed free-entry cultural sites (<i>Cine Teatro</i> and <i>Casa do Mineiro</i>); free-access mining site of two circuits: <i>Urban</i> and <i>Industrial</i>
	<i>Narrative</i>	Indoor: technical-industrial narrative dominant, social history secondary, strong educational infrastructure. Outdoor: Environmental impacts, remediation, geology, and biodiversity	Strong emphasis on social memory. Indoor: miners' lifestyle and artefacts, no permanent interpretive centre. Outdoor: Open-air, attraction-based distributed interpretation.
3. Tourism & Socio-Economic Impact	<i>Tourism</i>	Year-round structured cultural-scientific tourism; school-based flows; transport constraints	Leisure-heritage hybrid model; beach and nature tourism; educational activities; structural fragility; transport constraints
	<i>Socio-Economic Impact</i>	Stable and monitored visitor flows supporting a modest local service economy	Seasonal leisure-driven tourism producing incremental but limited economic gains
4. Art & Community Initiatives		Integrated artistic collaborations; institutional partnerships; moderate community co-production	Strong participatory art projects; deep grassroots involvement, and community-led initiatives
5. Planned Initiatives & Future Directions		Narrative integration and expansion of exhibition space; further remediation; renewable energy projects	Interpretative centre ambition; further remediation; renewable energy projects

3.1. Lousal

3.1.1. Post-Mining Realities and Management

Lousal's mining site covers approximately 175,000 m². The physical imprint of nearly a century of sulphide extraction remains evident across the site (See Figure 2). Waste-rock deposits, exposed tailings and persistent acid mine drainage have produced polluted lagoons, soil acidification, and generated metal contamination that once affected local groundwater, including the Corona stream (a tributary of the Sado River) (Luís et al., 2011). Remediation combined hydrological control measures, including water treatment basins, with soil requalification and geomorphological stabilisation. The approach aimed at impact management with the landscape transformation intentionally preserved as a material testimony to the site's mining history (Pinto, interview). Beside environmental impacts, post-mining out-migration and demographic ageing persist with population figures of roughly 250–280 residents (Pinto, interview).



Figure 2: General View of the Lousal Mining Site. Author. 22 October 2025.

Lousal operates under a public–private hybrid governance model in which the former mining company remains actively involved. The Lousal Cultural Complex is managed by the *Associação Centro de Ciência Viva do Lousal* (ACCVL), bringing together municipal, institutional and corporate partners who contribute personnel, funding and technical expertise (Pinto, interview). ACCVL is embedded in the national *Ciência Viva* network, which links local heritage communication and to a broader institutional infrastructure for science communication. According to Pinto, the association also participates in knowledge production and collaborates with applied research projects, which keeps its scientific content relevant and updated. In addition, it has longstanding partnerships with the Faculty of Fine Arts of the University of Lisbon which has embedded artistic practice across the site, both enriching its offer and connecting and engaging with local communities. In terms of funding, besides ticketing and merchandising revenue, and competitive grants or project funds derived from national and EU programmes, ACCVL receives a mix of institutional membership support, including the Municipality and regional bodies (e.g. *Comissão de Coordenação e Desenvolvimento Regional do Alentejo* – CCDR Alentejo has supported archival work and local documentation), and private partners such as *SAPEC Parques Industriais* and *Costa Terra*, while the Faculty of Sciences of the University of Lisbon provides personnel.

3.1.2. Heritage Interpretation and Communication

Heritage interpretation at Lousal reflects the institutional hybridity described above. The Mining Museum concentrates primarily on technical histories – mining machinery, compressed air (See Figure 3) and generator plants, geological services, and the chemical laboratory. It foregrounds extraction technologies and narratives of technical mastery, geological expertise, and industrial modernisation, while social history has less interpretive weight. The *Ciência Viva* centre complements the museum with scientific modules covering geology, mineralogy, crystallography, volcanism, resource mapping, radioactivity, biology and physics; it integrates interactive modules, educational laboratories and hands-on activities aimed at diverse age groups. Exhibitions explicitly link everyday artefacts to material flows and mineral dependency, using gamified displays and interactive quizzes to communicate how metals and non-metals underpin modern consumption. Nevertheless, broader conversations about mineral futures – including limits to recycling, geopolitical dependencies and scenarios beyond continued extraction – are largely absent from permanent displays and appear mainly through mediated encounters: guided tours, temporary exhibitions and event programming. Similarly, environmental impacts are sensed outside the exhibitions via the polluted lagoons, exposed waste heaps, and remediation infrastructure, which are interpreted on-site via panels and technical guides.

Community participation and heritage co-production are present in Lousal's interpretive structure, but their visibility remains uneven. Former miners and local contributors have supplied oral testimonies, guided tours, and practical labour (for example, the reconstruction of pedagogical mining models), yet these inputs are often under-documented in written exhibition material. In operational terms, ACCVL has invested in accessibility and multilingual mediation: guided tours, workshops and audio guides are provided in multiple languages (Portuguese, English, French, Spanish and German), and Portuguese Sign Language.

Beyond exhibition spaces, there are efforts to foreground ecological knowledge and ecosystem awareness within the site. The recent content update of *Aqui Há Bicho* (There Are Creatures Here) reflects a growing concern with communicating local biodiversity and ecosystems. Importantly, education constitutes a central communication pillar of ACCVL. The centre delivers structured programmes for schools, including the Science School (*Escola Ciência Viva / A Escola é Uma Mina*), which integrates activities in geology, chemistry, physics, and environmental sciences with site-specific learning in the former mining landscape. It also takes part in thematic initiatives such as Science and Technology Week, regional science fairs, and public events, communicating both science and contemporary environmental challenges.



Figure 3: Lousal's Mining Museum - Compressed Air Production Hall. Author. 22 October 2025.

3.1.3. Tourism and Socio-Economic Impacts

The socio-economic effects of the Lousal complex are multidimensional. Heritage and science programming generate sustained visitor flows – approximately 15,000–17,000 visitors annually and around 195,000 since 2010 (Pinto, interview)² – stimulating local services, hospitality, and accommodation, contributing to commercial activity beyond peak tourist seasons, while creating direct and indirect employment in cultural, educational, and tourism sectors. The site also receives international tourists from 15 to 25 countries each year, mainly from Spain, Germany, France, the Netherlands, and the United States.

Beyond tourism, educational initiatives – particularly the Science School – maintain a regular presence of school groups, teachers and families, while free access for local residents to the complex and its wooden walkways supports everyday recreational use and reinforces local attachment. The presence of a relatively young professional population has also increased demand for schooling and childcare, signalling modest demographic dynamism.

Nevertheless, these effects remain incremental, and the long-term viability of the cultural-scientific tourism model, along with its socio-economic contribution, depends on growing visitor numbers,

² <https://lousal.cienciaviva.pt/publicos/>

diversifying programming, and strengthening regional connectivity. Lousal's rural location and limited public transport restrict car-free access. Although ACCVL encourages organised group travel and has secured technical train stops, expanding and diversifying accessibility options remains essential to enhance inclusion and ensure long-term resilience.

3.1.4. Art and Community Initiatives

Artistic programming forms part of Lousal's broader cultural management strategy. These programmes have a dual role: they diversify the complex's cultural offer and open interpretive space for social, affective, and political dimensions of mining heritage that may otherwise remain secondary to technological and scientific framings. According to Pinto, integrating art into everyday visitor routes reactivates industrial ruins as spaces of cultural encounter, encouraging reflection and community engagement. Collaborations with the Faculty of Fine Arts have produced site-specific works in sculpture, painting, and installation, inserting affective and aesthetic registers into a setting otherwise dominated by technical and scientific narratives. Recent artistic residencies have addressed themes such as sensory histories of mining, territorial identity, and social memory (Oliveira & Vicente, 2023), introducing perspectives not always foregrounded in the permanent exhibitions. Finally, public performances, photographic exhibitions, and open-air film screenings extend the site's use beyond standard museum hours and tourist circuits, enriching local cultural experiences.

3.1.5. Planned Initiatives and Future Directions

Institutional actors at Lousal acknowledge existing gaps in the integration of social history and recognise the need to embed environmental narratives more systematically within permanent exhibitions. Pinto outlines intentions to expand exhibition space through the creation of a dedicated interpretive area explicitly combining social, geological, and environmental perspectives. This reflects an intention to move beyond reliance on guided mediation towards more self-sustained exhibition content.

Operational sustainability and decarbonisation are also prioritised. Photovoltaic systems are being introduced to supply the complex, accompanied by real-time displays of on-site production and consumption. These installations are conceived not only as infrastructural improvements but also as interpretive tools, linking operational practice to broader debates on energy transition.

Artistic programmes and community-led initiatives remain central to site renewal strategies. Planned residencies, workshops, and co-created public art projects aim to sustain local engagement and broaden interpretive discourses beyond predominantly technical, scientific, or tourism-oriented framings.

3.2. São Domingos

3.2.1. Post-Mining Realities and Management

The São Domingos mining complex presents a layered post-extraction landscape in which extensive industrial ruins and acidic lagoons coexist with a renovated townscape that continues to host cultural, educational and sporting facilities in a site of 2,000 hectares. Despite remediation and mitigation measures undertaken by EDM, the site's environmental condition remains severe, and soil contamination is considered irreversible (Alvarenga et al., 2022). To date, two of the six planned phases of environmental rehabilitation have been implemented, addressing surface runoff water, with the remaining phases of waste and draining management, decontamination of the Ribeira de Mosteirão Valley Downstream, and mining heritage valorisation still pending.³ Contamination, however, does not affect local aquifers or water used for human and animal consumption, and therefore does not generate acute concern among residents, who are generally well informed about environmental conditions (Marques, interview). The continued presence of inhabitants prevents complete abandonment, yet it also exposes demographic fragility, with a population of around 500 inhabitants and depopulation remaining a structural challenge. São Domingos thus occupies an intermediate position between abandonment and reinvention: its physical fabric bears the imprint of extraction and environmental degradation; its social fabric reflects demographic decline; yet its cultural life demonstrates persistence and ongoing experimentation.

³ <https://edm.pt/projetos/recuperacao-do-sistema-de-canais-de-recolha-de-aguas-de-escorrenca/>

Cultural management is primarily led by the Serrão Martins Foundation, working in close cooperation with the Municipal Council of Mértola. In practice, this configuration amounts to municipally sustained heritage management rather than a financially autonomous foundation or genuine public–private partnership. Although the landowner, *La Sabina*, is formally part of the governance structure, it plays a limited role, and the Foundation’s preservation and programming activities depend largely on municipal support (Marques, interview). Access to the mining complex and to the *Casa do Mineiro* is free of charge; revenue derives primarily from merchandise sales, guided visits, project-based funding, organised events, and concessions associated with the Tapada Grande river beach, originally constructed as a reservoir for ore washing. This arrangement reflects both commitment and constraint: there is clear local determination to sustain the mine as a cultural asset, yet financial and administrative resources remain restricted.

3.2.2. Heritage Interpretation and Communication

São Domingos operates largely as an informal open-air museum. The material ensemble is structured through two complementary circuits.⁴ The *Urban Circuit* includes the Church of São Domingos (Saint Dominic), the *Cinetatro*, Cross Brown football field, the former Administration Palace, the garden and housing of the English Quarter, the Workers’ Quarter, the Mine Police Station, the English Cemetery, the Musical Club, the Republican Centre of 5 October, and Tapada Grande. The *Industrial Circuit* extends across the 17-kilometre Ore Route (*Rota do Minério*), linking the Mine Entrance, the open pit (Figure 4), the headframe (locally known as the *Malacate*), the Railway Workshops, Moitinha, the Ore Dock at Pomarão, the Power Station, and the roasting furnaces at Achada do Gamo. Signposted with bilingual interpretative panels, these circuits organise spatial memory and structure visits and educational activities, maintaining the visibility of both the industrial infrastructure and the social fabric shaped by mining.



Figure 4: Open Pit at São Domingos Affected by Mine Acid Drainage. Author. 30 October 2025.

Despite this spatial organisation, the absence of a permanent interpretative centre remains a recognised limitation. The *Cinetatro* has functioned as the principal venue for heritage mediation, having previously hosted thematic exhibitions on mining history, labour struggles, and environmental degradation, displaying artefacts, tools, documents, and personal testimonies contributed by residents (Silva, 2012; Martins 2013). In 2019, the building underwent restoration works, and the permanent exhibition was dismantled. It now operates primarily as a flexible cultural venue hosting temporary exhibitions and a

⁴ <https://www.fundacaoserraomartins.pt/index.php?id=rota-do-minerio>

diverse programme of theatre, cinema, music and public events. Nevertheless, selected objects remain on display, including mineral samples, miners' helmets, a gasometer, medical instruments, a lantern, a locomotive identification plate ("Mina de São Domingos 1902 N°1"), original wooden benches, and the historic Cinemascope projector. The memory of that exhibition persists locally, alongside aspirations to establish a future purpose-built interpretative facility. Complementing this, the *Casa do Mineiro* is a reconstructed 16 m² miner's dwelling that recreates the cramped domestic conditions of a late nineteenth-century household (Figure 5).



Figure 5: *Casa do Mineiro* (Reconstructed Miner's Dwelling). Author. 28 October 2025.

Documentation and pedagogical mediation form a central pillar of the Foundation's strategy. The Documentation Centre and the *Casa do Mineiro* conserve tools, photographs and company records and are intended to serve as the nucleus for more systematic archival and research activity. Expanding the archival collection and recording oral testimonies are explicit objectives and ongoing processes.⁵ For school audiences, the Foundation has developed the *Maleta do Mineiro* – an educational toolkit co-produced with the local vocational school in Mértola – comprising games and interactive materials addressing social history, geology, anthropology and everyday life in the mining settlement.⁶ This decentralised and portable model of interpretation strengthens regional educational networks and positions São Domingos as a pedagogical resource rather than a static monument.

3.2.3. Tourism and Socio-Economic Impacts

Historically, the mine retained symbolic importance for former residents and their descendants, who return during the summer. This emotional return migration already sustained a degree of seasonal activity. Tourism was consolidated through targeted interventions. These included the rehabilitation of the former Supervisor's Palace of the British mining company and its conversion into the Hotel Alentejo Star, which played an important role in expanding local accommodation capacity. The upgrading of the Tapada Grande river beach significantly intensified visitation, introduced a new leisure dynamic, and diversified the visitor profile. At the same time, infrastructure and logistics were developed to support activities beyond cultural visits, including stargazing, canoeing, pedal boats, paddle sports, mountain biking and jeep circuits, offered by local businesses. This constitutes a hybrid model of tourism, combining leisure, nature, sport, and mining heritage,

⁵ <https://www.rostosdaaldeia.pt/beja/mina-de-sao-domingos/sara-ribeiro-respigadora/>

⁶ <https://www.fundacaoserraomartins.pt/index.php?id=mala-do-mineiro>

which encourages extending visits from short stops to multiple days. The increase in visitors has triggered secondary infrastructure needs: service areas for motorhomes, improvements to facilities, expansion of local accommodation and restauration offer, and provision of a more adequate signage and public transport connections. Socio-economic outcomes are incremental rather than transformative. Tourism has increased; accommodation has expanded; cultural participation has grown. Yet structural challenges, population decline, infrastructural limits, and funding dependency remain.

3.2.4. Art and Community Initiatives

The town hosts a variety of art and cultural endeavours. Notably, the Malacate project,⁷ funded through EEA Grants and led by the Cepa Torta collective, represents a distinct approach to post-mining valorisation: cultural activation through participatory art. Between 2021 and 2023, both local and international artists had residencies featuring workshops, theatrical exercises, art installations, and school activities, in which residents were active participants. Considered a success, the project was renewed for 2026 with a new set of activities. Furthermore, the creation of the Malacate Council – an informal deliberative group including artists and locals who discuss cultural projects – demonstrates a move toward participatory governance in cultural programming, aligning with contemporary heritage models that prioritise co-creation and community ownership. Other projects, according to Martins, include Futurama and Sementeira. Through its project *Cantexto*, Futurama brought musicians to São Domingos to create new ‘*modas*’ (music pieces for choral singing), later incorporated into the repertoire of local choirs.⁸ Sementeira organised artistic residencies at the mine, requiring artists to develop their work on-site in direct engagement with the local landscape and community. Beyond institutional and artistic projects, community associations remain active. The Choral Group organises gatherings; sports clubs host convivial matches, sometimes with teams from other mining regions in Portugal and Spain; hunting associations and gym groups maintain regular activities.

3.2.5. Planned Initiatives and Future Directions

A variety of projects and proposals point to different possible futures for São Domingos. Environmental rehabilitation remains a central priority yet pending due to funding constraints. The Foundation and the Municipality have articulated intentions for a formal interpretative centre to house the preserved artefacts and more effectively communicate the town’s history. As Marques explains, this ambition depends on securing funds, selecting an appropriate location, ensuring a sensitive architectural design within the classified ensemble, and obtaining approval from the landowner, *La Sabina*. Practical obstacles persist, notably the limited engagement of the landowner in heritage matters, which has already delayed a proposed archaeological intervention at the former power station due to pending authorisation.

Nevertheless, a potentially transformative initiative is private investment in renewable energy. Recent reports indicate that German investors, together with *La Sabina Green Energies*, are planning multi-phase installations – including photovoltaic (c.500 MW), wind (c.50 MW), and green hydrogen facilities – on the former concession area, with projected investments of up to €500 million.⁹ While these projects could bring economic benefits, they also raise critical questions about land use, ecological trade-offs, the distribution of gains, heritage preservation, and compatibility with tourism and remediation goals. Marques further notes that such developments would face significant technical constraints, including limited water availability, lack of conditions, and the common challenges of operating within a classified site.

Finally, both residents and Foundation staff – voiced during the interview and the INCOME public session – emphasise the need for initiatives that combine preservation with active engagement. Priorities include a permanent exhibition or interpretative centre, continued archival work and digitisation of company records, improved trail signage and visitor infrastructure, ongoing community involvement in planning, and the acceleration of remediation phases to allow safe and sustainable reuse of the site. Realising these objectives will require close coordination between the Municipality, the Foundation, the private owner, and external funding sources.

⁷ <https://www.malacate.pt/>

⁸ <https://www.futurama-alentejo.com/pt/arquivo/cantexto>

⁹ https://jornaleconomico.sapo.pt/noticias/alemaes-investem-28-milhoes-em-projeto-solar-na-mina-de-sao-domingos/?fbclid=IwY2xjawFAB8dleHRuA2FlbQIxMQABHeaOcfZE4WpGy0zc1g6B4hKkw9ruwQTnmGvnMkEYeGQ7KNjl-z85BfBJw_aem_ajD5BZruOJVpGy_qMr_OWQ&photo=2&sfnsn=mo

4. Conclusion

Documenting post-mining realities reveals layered complexities and persistent tensions. Environmental degradation continues despite remediation projects. Institutional arrangements are equally complex, involving collaborations and negotiations between former corporate actors, municipalities, foundations, national science networks, cultural associations and artistic collectives, each operating with distinct priorities, capacities and temporal horizons.

Although Lousal and São Domingos share a common geological history, comparable environmental legacies and demographic fragility, they have evolved through different governance structures and valorisation strategies. **Lousal** represents a structured rehabilitation model grounded in hybrid governance. Its positioning as a heritage site, science centre, and remediation example distinguishes it from more conventional single-purpose mining museums. The continued involvement of the former mining company, integration within the national *Ciência Viva* network, and stable institutional partnerships have enabled coordinated remediation, scientific communication, and diversified cultural programming. Heritage interpretation is concentrated within a managed and continuously updated complex, reflecting institutional reflexivity and long-term strategic planning, and suggesting a comparatively stable post-mining pathway.

São Domingos reflects an urban/industrial landscape case. Environmental remediation remains incomplete with a vastly larger mining concession, more extensive landscape transformation, and heavier pollution. Its governance depends largely on municipal capacity and community mobilisation, with limited engagement from the private landowner. Interpretation is spatially distributed across the site, supported by participatory cultural initiatives and educational tools, yet it lacks a dedicated interpretative centre. Tourism follows a hybrid model combining heritage, leisure, and nature, which has expanded visitation, but remains strongly seasonal and structurally constrained. The prospect of large-scale renewable energy installations introduces further uncertainty to the future of the town.

In both cases, tourism is challenged by seasonality and its infrastructure remains limited. Local businesses operate within limited markets, accommodation, catering, and transport infrastructures are insufficient for large-scale expansion, and promotional strategies largely remain regional in scope. Furthermore, socio-economic realities remain more modest than the transformative narratives of heritage-led development. Demographic decline persists, along with challenges in terms of access to healthcare, public transport, educational services and everyday infrastructure. While cultural programming may reinforce local attachment and visibility, revitalisation remains fragile without demographic consolidation and provision of basic services. These conditions underline the need for broader territorial coordination, improved connectivity, and long-term investment frameworks capable of situating heritage initiatives within wider development strategies. The cases demonstrate that effective post-mining transition requires alignment between environmental remediation and cultural activation, governance arrangements that balance public and private interests, and heritage practices that engage critically with resource histories while contributing to economic diversification.

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Industrial Heritage as a Redevelopment Platform: Multi-Site Insights from Estonian Oil Shale Mining Region

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Abstract

Post-mining regions face a dual challenge: managing environmental and safety legacies while enabling credible economic redevelopment that can absorb labour, attract investment, and retain regional identity. This article (presentation) positions industrial heritage as enabling infrastructure for redevelopment, with a specific emphasis on how post-mining assets can be recombined into new local “platforms” that support entrepreneurial activity and, where feasible, industrial symbiosis.

The research asks how three Estonian oil shale post-mining reuse trajectories can be assessed as economic-redevelopment models and as potential anchors for symbiotic linkages. The comparative case set comprises Kiviõli’s adventure- and recreation-led redevelopment of oil shale heritage landscapes, the emerging motopark and viewpoint development on the Estonia mine waste rock heap, and the Aidu watersport/rowing-centre redevelopment of an oil shale open cast mine.

Methodologically, the study combines planning and policy review with stakeholder engagement and site-level assessment focused on legacy and business opportunity. The analysis explicitly tracks where redevelopment value is created (complementary service ecosystems and place-based branding) and where symbiosis opportunities may realistically emerge through co-location, shared utilities, and the repurposing of industrial surfaces, illustrated by the parallel emergence of new-energy infrastructure on post-mining industrial land.

The expected contribution is a decision-oriented framework that helps closure planners and regional developers evaluate post-mining industrial heritage not only as a conservation object but as a redevelopment asset with measurable economic outputs and identifiable pathways toward symbiosis-enabled upgrading.

Keywords: Mining Heritage, Oil Shale, Circular Economy, Economic Redevelopment, Industrial Symbiosis

1. Introduction

Post-mining regions increasingly operate at the intersection of closure obligations and regional development imperatives. Beyond stabilising landforms and managing long-term environmental and safety risks, these regions must also generate credible pathways for economic renewal. Pathways that can attract investment, create employment, and sustain local identity after extraction declines. In this context, post-mining industrial heritage should not be treated solely as an object of conservation, but as a potential redevelopment asset: a set of material and spatial resources (landforms, surfaces, access routes, and infrastructure) that can be recombined into new place-based platforms for entrepreneurship, services, and, where enabling conditions exist symbiosis-enabled upgrading through co-location and shared utilities.

1.1. Post-mining transition as a dual challenge

Post-mining regions face a dual technical and socioeconomic challenge. On the one hand, closure and post-closure require long-term management of environmental, safety, and liability issues. On the other hand, regional actors must enable credible economic redevelopment that can absorb labour, attract investment, and sustain a coherent identity after extractive activity declines. In practice, these challenges become intertwined:

unresolved legacy constraints can block investment, while weak redevelopment pathways can undermine public support and long-term stewardship.

A persistent gap in post-mining practice is that redevelopment is often framed as “aftercare” or “land reuse” without an explicit theory of how local economic value is created, scaled, and sustained. The result is a mismatch between (i) closure planning, which tends to prioritise stability and risk control, and (ii) regional development, which depends on investable propositions, operator models, and complementary service ecosystems. This study addresses that gap by treating industrial heritage as enabling infrastructure for redevelopment rather than as a static conservation object.

1.2. Industrial heritage as a redevelopment platform and the role of symbiosis

Industrial heritage has typically been discussed through conservation, interpretation, and adaptive reuse, with attention to how heritage can contribute to place identity, tourism, and regeneration. A useful extension for post-mining contexts is to conceptualise heritage assets (landforms, structures, access routes, utilities, and industrial surfaces) as a platform: a modular base that can host multiple complementary activities over time. This platform view shifts the unit of analysis from a single “project” to an evolving local system of operators, services, events, and users. Where value is created through complementarities and repetition rather than one-off investments.

Where conditions permit, the platform can also enable industrial symbiosis, understood as a cooperative advantage created through geographically proximate exchanges and shared systems (e.g., utilities, infrastructure, space, or by-products). The industrial symbiosis literature emphasises that proximity and collaboration are key enablers, but that not every site is a realistic candidate; screening for feasible pathways is therefore essential. (Chertow, 2000) In post-mining regions, symbiosis can extend beyond classic by-product exchanges to include shared utilities, shared infrastructure, and the repurposing of industrial surfaces for new energy or circular activities, provided legacy constraints, governance, and operator models are aligned.

1.3. Study aim, questions, and contribution

This study asks: How can post-mining industrial heritage trajectories be assessed as economic-redevelopment models and as potential anchors for symbiotic linkages? The study develops and applies a comparative, decision-oriented assessment across three Estonian oil shale post-mining reuse trajectories: (1) Kiviõli’s adventure- and recreation-led redevelopment of heritage landscapes, (2) the emerging motopark and viewpoint development on the Estonia mine waste-rock heap, and (3) the Aidu watersport/rowing-centre redevelopment of an open-cast mine. These three study areas are shown in Figure 1.

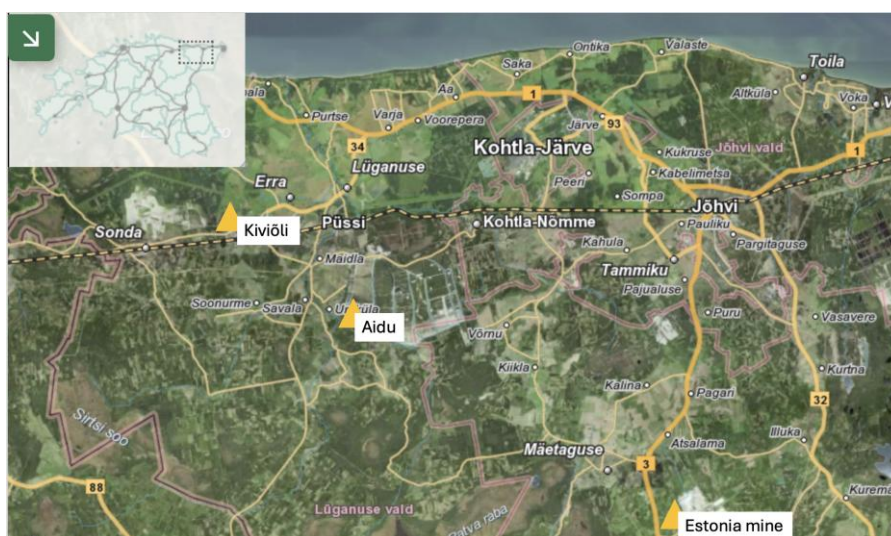


Figure 1 Three study areas in the Estonian oil shale deposit

The expected contribution is a decision-oriented framework that helps closure planners and regional developers evaluate industrial heritage as a redevelopment asset with (i) measurable economic outputs, (ii)

identifiable value-creation mechanisms (service ecosystems and place-based branding), and (iii) realistic pathways toward symbiosis-enabled upgrading rather than aspirational “one-size-fits-all” circularity.

2. Materials and Methods

2.1. Comparative case design and selection logic

The study uses a comparative case design to examine three post-mining reuse trajectories that differ in redevelopment logic, maturity, and asset type, while sharing a common extractive context (oil shale) and regional legacy conditions. The case set was selected to maximise variation along three dimensions: (i) dominant value proposition (adventure/recreation vs motorsport/viewpoint vs watersport/rowing), (ii) stage of redevelopment (established vs emerging), and (iii) heritage asset configuration (landscapes and landforms vs waste-rock heap vs open-cast waterbody). This variation enables analytic comparison of how platform value is produced and how symbiosis opportunities may (or may not) emerge.

2.2. Assessment protocol: from “legacy constraints” to “business opportunity”

Site-level assessment was structured around two lenses: legacy constraints and business opportunity. The legacy lens captures factors that can impose long-term costs or block investment (e.g., safety, stability, contamination management, access restrictions, monitoring obligations, and liability clarity). The opportunity lens captures factors that increase investability and operational feasibility (e.g., connectivity, utilities, visibility, modular spaces, event capacity, and compatibility with complementary services). Site observations were recorded using a standardised data collection method, supported by photographs and basic mapping.

2.3. Analytical logic: tracking value creation and screening symbiosis feasibility

Analysis proceeded in two linked steps. First, each case was assessed for how redevelopment value is created, operationalised through (i) the density and diversity of complementary service ecosystems (operators, suppliers, hospitality, events, education, maintenance), and (ii) place-based branding mechanisms (narratives, signature experiences, repeat visitation, and external visibility). Second, each case was screened for symbiosis feasibility using a pragmatic definition of symbiosis opportunities as those that can realistically emerge through (a) co-location, (b) shared utilities, and (c) repurposing of industrial surfaces. The screening explicitly distinguishes “conceptually attractive” ideas from those supported by enabling conditions such as governance clarity, infrastructure availability, and operator incentives.

2.4. Framework development: decision-oriented synthesis across cases

The decision-oriented framework was developed through cross-case synthesis, translating qualitative evidence into a structured set of evaluation dimensions and practical decision questions. Iteration occurred by comparing (i) what the framework would recommend for each site, and (ii) what is currently happening or planned in practice, to ensure the framework is both analytically coherent and operationally usable for planners and developers.

3. Results and Discussion

All three case sites demonstrate that post-mining land can be repurposed into functioning, economically oriented uses rather than remaining a closure burden. While each trajectory differs in maturity and core value proposition: adventure and recreation (Kiviõli), an emerging motopark and landmark viewpoint (Estonia mine waste-rock heap), and a watersport/rowing centre (Aidu). They share a common logic: industrial heritage assets are recombined into new place-based “platforms” that attract users, enable complementary services, and gradually build external visibility. The results section, therefore, uses the three cases to show (i) where redevelopment value is created through service ecosystems and branding, and (ii) under what conditions symbiosis options (co-location, shared utilities, repurposed industrial surfaces) are realistic rather than aspirational.

3.1. Case A – Kiviõli: adventure- and recreation-led redevelopment platform

Kiviõli represents an established trajectory in which post-mining heritage landscapes are recombined into an adventure- and recreation-led platform. The redevelopment logic is experience-centric: the heritage landscape itself serves as the core asset, while value is amplified through complementary services such as events, hospitality, equipment rental, instruction, maintenance, and supporting enterprises, such as Kiviõli Seikluspark. This configuration illustrates how an industrial heritage asset can shift from “site” to “system,” where revenue and employment potential depend on repeat visitation, seasonal programming, and the reliability of the service ecosystem.

Kiviõli Seikluskeskus, the site operator, developed the semi-coke hill between 2001 and 2013, converting the ~90 m anthropogenic landform into a ski and adventure tourism facility. This redevelopment established a multi-season operating model, enabling both winter (ski-based), as shown in Figure 2 and summer (adventure/leisure), as shown in Figure 3, activities and thereby supporting year-round site use. (Kiviõli Seikluskeskus, 2026)

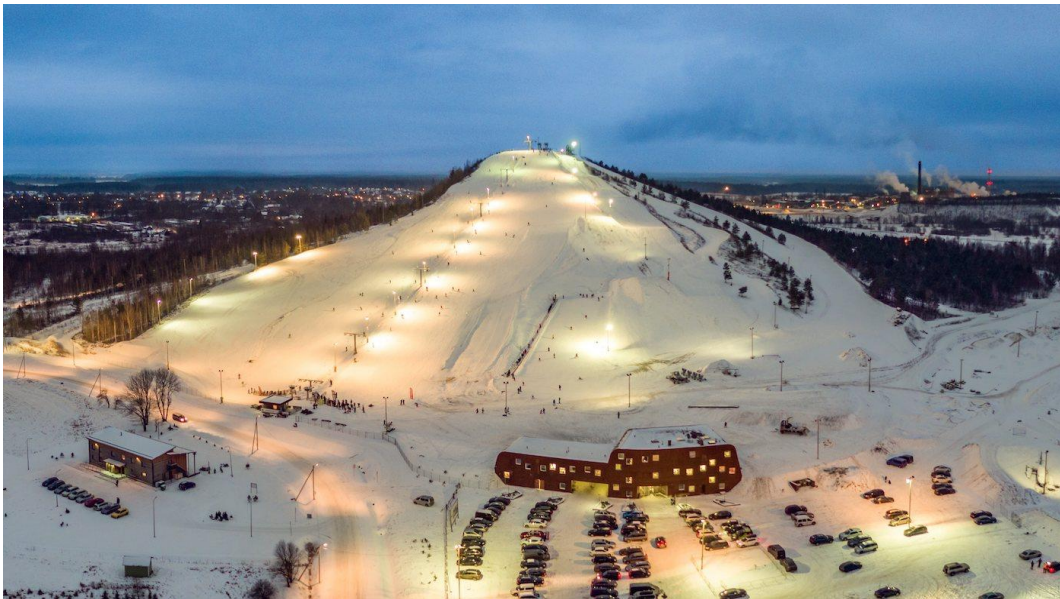


Figure 2 Kiviõli adventure centre in winter (photo by Kiviõli Seikluskeskus)



Figure 3 Kiviõli adventure park in summer (photo by Kiviõli Seikluskeskus)

From a platform readiness perspective, Kiviõli's model highlights the importance of access, safety management, and operational clarity. Where heritage landscapes are used actively, safety and liability management must be embedded into the operating model rather than treated as an external compliance burden. The case also suggests that the most immediate economic value may come from service complementarities rather than from industrial re-use in the narrow sense. Symbiosis opportunities, therefore, are likely to be "light-industrial" or infrastructure-sharing in nature (e.g., shared utilities, shared logistics, multi-use spaces), unless there is a clear anchor tenant or adjacent industrial demand that can support physical exchanges.

3.2. Case B – Estonia mine waste-rock heap: emerging motopark and viewpoint trajectory

The Estonia mine waste-rock heap case represents an emerging redevelopment pathway focused on motopark and viewpoint development. As an early-stage trajectory, it has primary analytical value in showing how "path dependence" is created: early design and governance choices can either preserve optionality for future complementary uses or lock the site into a narrow, fragile revenue model. In particular, the site's visibility and distinct landform can support place-based branding, but long-term viability depends on whether complementary services (events, visitor services, training, maintenance, partnerships) are planned as a deliberate ecosystem rather than assumed to emerge organically.

The Estonia mine waste-rock heap ("motomägi") (Figure 4) is being repurposed into an experience-oriented destination under the Estonia Elamuspark initiative. The operator, MTÜ Estonia Elamuspark, initiated active development in early 2024 and announced the first public open day for late May 2024. During this event, visitors could reach the summit via a long serpentine cycling route and take part in on-site activities, including a newly introduced cross-country running event. The site's physical infrastructure, specifically the motor track and the serpentine access route to the summit, is distinctive in the Estonian context, highlighting how an anthropogenic landform can be mobilised as a redevelopment asset rather than remaining a residual closure feature. (Põhjarannik, 2024)

For closure planners and developers, this case foregrounds two practical issues. First, legacy constraints (stability, safety, access control, monitoring) can determine not only what uses are permitted, but also what operator models are feasible. Second, if symbiosis is an objective, it should be "designed in" through infrastructure and spatial decisions that enable co-location and shared utilities. Without such enabling investments, symbiosis remains rhetorical. The emerging nature of this trajectory makes it a strong candidate for applying the decision-oriented framework proactively: it is easier to build platform readiness than to retrofit it later.



Figure 4 Estonia mine waste rock heap as a motopark (photo by Põhjarannik)

3.3. Case C – Aidu: watersport/rowing-centre redevelopment of an open-cast mine

Aidu represents a water-based redevelopment model in which an open-cast mine landscape is repurposed as a watersport and rowing-centre trajectory. Here, the core asset is a waterbody and associated landscape configuration that can host sport, training, and events. The value-creation mechanism again relies on complementarities: sporting activity alone rarely sustains a full local economy, but it can anchor related services (accommodation, food services, event logistics, coaching, equipment, and regional visitor itineraries). This case thus demonstrates how a post-mining landscape can become a brandable “signature asset” that supports a broader service economy.

The transformation of the Aidu oil shale open cast mine into a rowing centre began as a visionary initiative aimed at repurposing the vast, water-filled excavation voids into a functional and attractive sports venue (Kruuse, 2009). The concept was driven by the site’s unique geological and hydrological features, which made it especially suitable for water-based activities. The linear shape, depth, and sheltered nature of the former mine voids offered the potential to create long, calm stretches of water ideal for rowing competitions and training (Figure 5). (Karu, 2025)

The case also illustrates how legacy constraints shape opportunity. Water-based reuse introduces distinct safety, maintenance, and governance requirements compared to landform-based recreation. The long-term viability of the platform depends on clarity of responsibilities for monitoring, maintenance, and risk management, as well as on the operator’s ability to create repeat demand beyond one-off events. Symbiosis opportunities in such a setting are most plausible through shared utilities and co-located functions that benefit from the site’s space, access, and visibility, rather than through complex by-product exchanges.



Figure 5 Aidu rowing channel (photo by Eesti Sõudeliit)

3.4. Cross-case comparison: three platform logics and where economic value is created

Across the three cases, three platform logics are visible: (i) an experience-ecosystem platform (Kiviõli), (ii) an emerging landmark-and-events platform (waste-rock heap), and (iii) a sport-and-training platform (Aidu). In all three, economic value is created primarily through complementary service ecosystems and place-based branding rather than through a single dominant revenue stream. The practical implication is that post-mining redevelopment strategies should be evaluated by their capacity to sustain an ecosystem of operators and services over time, not only by their capital expenditure or the symbolic appeal of heritage.

A second cross-case pattern is that platform success depends on the alignment of three conditions: (a) physical readiness (access, utilities, usable surfaces), (b) governance readiness (liability clarity, permissions, long-term management), and (c) market readiness (repeat demand and partnerships). Sites that are strong on branding but weak on governance or utilities risk becoming “one-off attractions” with limited employment absorption. Conversely, sites that are operationally robust but lack a clear narrative may fail to attract demand.

3.5. Where symbiosis is realistic: screening pathways rather than assuming circularity

Industrial symbiosis is frequently invoked in post-industrial transitions, but the cases underline the need for realism. A pragmatic approach is to distinguish between (i) symbiosis as physical exchange (materials/energy/water/by-products), (ii) symbiosis as shared utilities and infrastructure, and (iii) symbiosis as spatial co-location that reduces costs and enables complementarities. The industrial symbiosis literature emphasises collaboration and proximity as key enablers, but also implies that successful symbiosis requires suitable anchors, governance, and transaction capacity.

In post-mining settings, the most plausible near-term pathways often involve shared utilities and the repurposing of industrial surfaces, especially as many regions increasingly consider disturbed industrial land for renewable energy deployments, thereby reducing land-use conflict and leveraging grid proximity. For the cases in this study, symbiosis is therefore treated as an option set: an upgrading pathway that becomes feasible when specific enabling conditions are met (e.g., available grid connection, operator incentives, multi-tenant governance, and manageable legacy liabilities). This stance protects planners and developers from over-promising “circularity” while still identifying actionable routes to symbiosis-enabled upgrading.

3.6. Decision-oriented framework: evaluating heritage as redevelopment infrastructure

Based on the cross-case synthesis, the study proposes a decision-oriented framework that evaluates post-mining industrial heritage along four dimensions: (1) legacy constraints and liabilities, (2) platform readiness, (3) value-creation model, and (4) symbiosis option set. The framework is designed for use by closure planners and regional developers as a structured conversation tool and an assessment scaffold, not as a purely quantitative index. It enables decision makers to (i) identify where measurable economic outputs are most likely, (ii) clarify what enabling investments are required, and (iii) specify whether symbiosis is realistic in the near term or only as a longer-term upgrade path.

Operationally, the framework can be applied in five steps. First, define the asset boundary (what is included in the “platform” and what is external to it). Second, map legacy constraints and governance responsibilities that affect investability and operating cost. Third, specify the intended value creation mechanism (experience ecosystem, landmark-events, training hub, multi-tenant industrial reuse, etc.) and test whether complementary services are likely to emerge. Fourth, screen symbiosis pathways using co-location, shared utilities, and industrial surface repurposing as the primary categories. Fifth, translate the outcome into an action plan that assigns responsibilities to closure planners, municipalities, and operators, including “minimum viable platform” investments that preserve optionality.

4. Conclusion

This study reframes post-mining industrial heritage as enabling infrastructure for redevelopment by treating heritage assets as recombinable platforms. Across three Estonian oil shale reuse trajectories, the analysis shows that economic value is created primarily through complementary service ecosystems and place-based branding, while symbiosis opportunities require careful screening and enabling conditions rather than assumption. The cases demonstrate that platform success depends on alignment between physical readiness, governance readiness, and market readiness; weaknesses in any one dimension can constrain employment absorption and investment credibility.

The proposed decision-oriented framework provides a practical way to evaluate heritage assets as redevelopment infrastructure with measurable outputs and transparent trade-offs. It is particularly useful for emerging trajectories, where early governance and infrastructure decisions strongly shape long-term optionality and the feasibility of symbiosis-enabled upgrading.

4.1. Recommendations for closure planners and regional developers

For closure planners, the key recommendation is to treat redevelopment enablement as part of closure readiness: clarify liabilities, access regimes, and long-term management responsibilities to reduce transaction costs for operators and investors. Where possible, design closure measures to preserve platform optionality (e.g., maintain access, protect usable surfaces, and avoid unnecessary fragmentation of land control). For regional developers and municipalities, the priority is to move beyond “single-project” thinking and plan for complementary service ecosystems, including operator partnerships, event programming, and skills development, to stabilise seasonal demand.

For both groups, symbiosis should be approached as an incremental upgrade pathway. Start with feasible forms, shared utilities, shared infrastructure, and co-location, then expand toward more complex exchanges only when anchor tenants, governance capacity, and monitoring obligations are sufficiently mature. This staged approach helps avoid the common failure mode where “circular economy” language outruns the site’s real constraints and capabilities.

Acknowledgments

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Maden Sahalarında Kültürel Miras Etki Değerlendirme Adımları ve Profesyonellerin Rolü

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Özet

Madencilik faaliyetlerinin kültürel miras üzerinde yaratabileceği geri dönülmez etkiler nedeniyle KMED' in bir maden projesine ait yaşam döngüsünün hangi aşamasında başlatılması gerektiği, hangi aşamalara dek sürdürüleceği kritik öneme sahiptir. KMED; kapsamın belirlenmesi, kültürel mirasa yönelik tespitler, tespitlerin değerlendirilmesi ve analiz edilmesi, etkilerin yaratacağı olumsuzluklar, bu olumsuzluklar karşısında alınacak önlemler ve tüm bu süreçleri bünyesinde barındıran bir raporun hazırlanması gibi bütüncül ve yaşayan bir süreçten oluşmaktadır. Doğru yürütülen KMED çalışmaları sadece kültürel miras açısından pozitif fayda sağlamakla kalmaz aynı zamanda proje faydalanıcılarına da önemli avantajlar sunar. Rio Tinto'nun Oyu Tolgoi Projesi ve Juukan Gorge vakası gibi uygulama örnekleri maden projelerinde KMED süreçlerinin ve bu süreçte profesyonellerin üstlendiği rollerin önemini açıkça ortaya koyması açısından önem arz etmektedir.

Anahtar Kelimeler; Kültür, Kültürel Miras, Kültür Varlığı, Kültürel Mirasın Korunması, Kültürel Miras Etki Değerlendirme

Cultural Heritage Impact Assessment Steps in Mining Areas and the Role of Professionals

Abstract

Given the potentially irreversible impacts of mining activities on cultural heritage, it is of critical importance to determine at which stage of a mining project's life cycle the Cultural Heritage Impact Assessment (CHIA) should be initiated and through which phases it should be maintained. CHIA constitutes a holistic and dynamic process encompassing scoping; the identification of cultural heritage assets; the evaluation and analysis of findings; the assessment of adverse impacts; the development of mitigation measures in response to such impacts; and the preparation of a comprehensive report integrating all these components. When properly implemented, CHIA not only generates positive outcomes for the protection and sustainable management of cultural heritage but also provides significant benefits to project stakeholders. Illustrative examples, such as Rio Tinto's Oyu Tolgoi Project and the Juukan Gorge case, clearly demonstrate the importance of CHIA processes in mining projects, as well as the critical roles undertaken by professionals throughout these processes.

Keywords; Culture, Cultural Heritage, Cultural Asset, Protection of Cultural Heritage, Cultural Heritage Impact Assessment

1. Giriş

Küresel ekonomik büyüme, sanayileşme ve nüfus artışı, ihtiyaçların karşılanabilmesi için hammadde talebini her geçen yıl daha da artırmaktadır. Bu durum madencilik faaliyetlerinin ölçeğini ve yoğunluğunu genişletmektedir.

Madenlerin ekonomik bir değere döndürülmesi amacıyla yürütülen modern madencilik faaliyetleri somut ve somut olmayan kültürel miras unsurları üzerinde doğrudan ya da dolaylı olarak olumlu veya olumsuz etkiler yaratabilirler.

Kültürel mirasın korunması sadece kültürel varlıkların devamlılığı açısından değil; toplumsal kimliklerin, kültürel çeşitliliğin, tarih bilincinin ve sosyal uyumun sürdürülebilirliği bakımından da öneme sahiptir. Tam bu noktada Kültürel Miras Etki Değerlendirmesi (KMED) teknik, etik, sosyal, hukuki ve bilimsel boyutlarıyla çok disiplinli bir çerçevede yürütülmesi gereken bir değerlendirme ve aksiyon planları hazırlama aracı olarak öne çıkmaktadır. Bu nedenle madencilik faaliyetlerinde kültürel mirasın korunmasına yönelik “etki değerlendirme çalışmaları”, projelerin erken aşamalarından itibaren sistematik, şeffaf ve uluslararası iyi uygulamalara dayalı bir yaklaşımla ele alınmalı ve etki değerlendirme sonuçlarına göre tasarlanan aksiyon planları hayata geçirilmelidir. Sürecin etki değerlendirme sonuçlarına göre yönetilmesi, kültürel mirasın madencilik sonrası faaliyetlerinde kapsama dahil edilebilmesine olanak sağlar. Aksi takdirde, madencilik faaliyetleri sırasında kültürel mirasın tamamen yok olması bir sonuç olarak karşımıza çıkabilir.

2. Maden Projelerinde Kültürel Miras Etki Değerlendirmesi Adımları

Maden sahaları yalnızca ekonomik değer taşıyan alanlardan ibaret değildir. Bugün ihtiyacımız olan pek çok cevher tarih boyunca farklı toplumların da yaşamsal ihtiyacı olmuştur. Bu ihtiyaçları karşılamak isteyen toplumlar maden sahalarının bulunduğu coğrafyaya yerleşerek o günün tekniklerine uygun biçimde cevheri çıkarmış ve kullanmıştır. Bu durum maden sahalarının tarih boyunca kültürel açıdan şekillenmesine, toplumsal belleğin izlerini barındıran kültürel peyzaj sahalarına dönüşmesine sebep olmuştur. Bu durum modern madencilik faaliyetlerinin yürütüldüğü maden sahalarında somut ve somut olmayan kültürel miras unsurları ile karşılaşma potansiyelini de beraberinde getirmiştir.

Maden projeleri; amaç, kapsam, yatırım niteliği ve işletmeye etkisi bakımından “yeni yatırım projeleri, tevsi projeleri ve idame projeleri” olarak üç ana gruba ayrılırlar. Bu projelerden elde edilecek cevherler ise “yerüstü (açık ocak) madenciliği ve “yeraltı madenciliği” olmak üzere iki tür yöntem kullanılarak maden sahalarından çıkarılırlar. Amacı, kapsamı ve niteliği fark etmeksizin tüm maden projeleri “konsept, planlama, inşaat, işletme, işletmeden çıkarma ve rehabilitasyon (iyileştirme)” aşamalarından oluşan bir yaşam döngüsüne sahiptir.

Madencilik faaliyetleri bu yaşam döngüsünün farklı aşamalarında kültürel miras üzerinde farklı etkiler yaratabilir. ICOMOS’ a göre etki değerlendirme, önerilen eylemlerin kültür varlıkları üzerinde yaratabileceği sonuçları araştırarak karar verme süreci olarak da tanımlanır.



Şekil 1.

Bu karar verme sürecinde amaç, madencilik faaliyetlerinin kültürel miras üzerinde geri dönüşü olmayan olumsuz etkilerini ortadan kaldırmaktır. KMED, seçme, kapsam belirleme, mevcut durum tespiti, proje ve alternatiflerinin incelenmesi, etkilerin öngörülmesi ve tanımlanması etkilerin değerlendirilmesi, etkilerin

Araştırılmalarda harita-tabanlı yerel envanter taramaları, bölgede daha önce gerçekleştirilmiş bilimsel çalışmalara ait yayın taramaları ile projenin planlandığı coğrafi alanın tarihi arka planı da araştırılmalıdır. Bu durum kültür varlıkları açısından potansiyelin önceden anlaşılmasını sağlayarak planlanan proje sahasında nelerle karşılaşılabilceği konusunda ön fikir vermesi açısından önemlidir.

2.2. Planlama Aşaması

Bir maden projesinde planlama aşaması aynı zamanda kapsamlı bir KMED' in de başladığı aşamadır. "Kapsam belirleme, mevcut durum tespiti, proje ve alternatiflerinin değerlendirilmesi, etkilerin ön görülmesi ve tanımlanması, etkilerin değerlendirilmesi, hafifletme ve iyileştirme ile tüm bu çalışmaların raporlanması" gibi KMED adımları madencilik yaşam döngüsünün planlama aşamasında gerçekleştirilir.

2.2.1. Kapsam Belirleme

Kapsam belirleme, KMED' in hazırlanmasındaki ilk esaslı adımdır. KMED' in sınırlarını belirleyen ve her aşamada yapılacak analizlerin temelini oluşturan bu sistematik adımda etki değerlendirmesinde kullanılacak verilerin neler olduğu, etkilerin kaynakları, coğrafi alanı, ortaya çıkacağı zaman dilimi (süresi), etki değerlendirmesinde ihtiyaç duyulan uzmanlıklar ve görev tanımları ile eldeki temel bilgilerin yeterli olup olmadığı araştırılır.

Ayrıca bu adımda proje etki alanı da dâhil olmak üzere proje sahasının kültürel miras potansiyeli ortaya konarak etki değerlendirmesinde ele alınacak kültürel miras unsurlarının genel çerçevesi oluşturulur. Paydaş istişareleri ve alınan geri bildirimlerin KMED sürecine sistematik biçimde entegre edilmesi sağlanır. Bununla birlikte, projenin tüm aşamalarında kültürel miras üzerinde ortaya çıkabilecek etkiler tanımlanır, önemli ve önemsiz etkiler ayrıştırılarak listelenir ve bu ayrımın gerekçeleri analitik olarak açıklanır. Tüm bu unsurlar kapsam belirleme sürecinde detaylandırılarak raporlanır.

Kapsam belirleme faaliyetleri çerçevesinde, KMED'i yürütecek uzman ekibin yetkinliklerinin tanımlanması, mevcut bilgi ve veriler ışığında alanın güncel durumunun değerlendirilmesi ve buna bağlı olarak ek veri ihtiyaçlarının belirlenmesi sağlanır. Etki değerlendirmesinde kullanılacak veriler neyin ne kadar etki değerlendirmeye dahil edileceğine veya kapsam dışı bırakılacağına karar vermemizi sağlar.

2.2.2. Mevcut Durum Tespiti

Proje ile etkileşim içinde olan kültürel miras varlıklarının mevcut durumu, kültürel mirası mevcut durum itibariyle etkileyen koşullar, önerilen projenin gelecekte olmaması durumunda kültürel miras üzerinde ortaya çıkabilecek değişiklikler, kültürel miras varlığının nasıl yönetildiği ve korunma durumu gibi bilgiler bu adımda ele alınır ve mevcuttaki kültürel miras ile ilgili bilgi toplama süreci tamamlanır. Derlenen bu bilgi daha sonra, etki değerlendirmesi için altlık olarak kullanılır. Bu nedenle mevcut durumunun tespiti kapsamlı ve sistematik bir metodoloji ile somut ve somut olmayan miras unsurlarını kapsamlı biçimde ele almalıdır. Uzmanlar mevcut durum tespiti yaparken madencilik faaliyetlerine yönelik alternatifler dahil, proje ve etki alanını kapsayacak şekilde masa başı ve saha çalışmalarını bir arada yürütmelidir.

Somut kültür varlıklarının tespitinde; arkeolojik yüzey araştırmaları yöntemlerinin dışında, ileri jeofiziksel teknolojiler ve dijital veri araçları (LIDAR, drone, fotogrametri vb.) çalışmalara entegre edilebilir. Topografik, coğrafi ve mekânsal anlamda yürütülecek bu analizler kültürel varlıkların koruma alanlarının belirlenmesinde ve maden sahası planlamasının kültürel hassasiyetlere uygun olarak şekillendirilmesinde yol gösterici olacaktır. Tespit sadece somut kültür varlıklarını kapsamamalıdır. Etki alanı içindeki halkın yerel ve geleneksel davranışları, sözlü tarihi ve her türlü etnografik verisi toplanarak somut olmayan kültürel miras çalışmaları da yürütülerek tespite dahil edilmelidir. Bu sayede kültürel mirasa yönelik data bütüncül bir anlayışla toplanmış olacaktır.

Tespit çalışmalarında toplanan veriler çoğu zaman kültürel miras envanterlerine yeni bilgiler kazandıracaktır ve bunlar üzerinde oluşabilecek geri döndürülemez kayıpların önlenmesini de sağlayacaktır.

2.2.3. Önerilen Proje ve Alternatifler

Bu adımda, önerilen projenin planları, coğrafya üzerinde oluşturacağı değişime ait görselleri, projenin tasarım, hazırlık, inşaat, işletme ve yenileme aşamasına kadarki süreci ele alan planlar, tanımlanmış bir

coğrafi alan içindeki kültürel mirasın üzerinde, projenin yaratabileceği olası etkiler (olumlu veya olumsuz) tanımlanır. Projenin kültürel miras üzerinde yaratabileceği olası olumsuz etkileri önleyecek veya azaltabilecek alternatiflerin olup olmadığı, uygulanabilir olup olmadığı bu adımda ele alınmalıdır. Bu süreç katılımcı ve proaktif bir yaklaşımla yönetilmelidir. Gerekirse farklı kurum ve bilgi kaynakları ile iletişime geçilerek projenin tasarımında alternatiflerin kullanılması veya yeni alternatifler oluşturulması gibi ön çalışmalar bu aşamada değerlendirilebilir.

2.2.4. Etkilerin Öngörülmesi, Tanımlanması ve Değerlendirilmesi

Bu kritik adımda; proje faaliyetlerinin somut ve somut olmayan kültürel miras varlıkları üzerindeki olası sonuçlarının sistematik olarak analiz edilmesi amaçlanır. Etkinin nerede, ne zaman ve nasıl ortaya çıkabileceğini tanımlayan bu adım salt bir “risk tespiti” süreci değil, mirasın bütünsel olarak anlaşılması, korunması ve geleceğe aktarılması için gerekli olan analitik bir çerçevedir.

Öngörü ve tanımlama yalnızca bilinen miras unsurları için gerçekleştirilmemelidir. Kültür varlıklarının bir bölümü zaman içerisinde toprak altında kalarak (arkeolojik miras gibi) gizlenmiş olabilir. Deneyimli uzmanlar etkiler için öngörü ve tanımlama yaparken bu potansiyelleri de hesaba katmalıdır.

Bir maden projesinin kültür varlıkları üzerinde “doğrudan, dolaylı ve kümülatif” etkileri olabilir. Tanımlama yapılırken bu etki türleri değerlendirmeye alınmalıdır. Etkileri belirlemek için genellikle uzman görüşü kullanılır. Uzman görüşüne yardımcı olarak renk kodlu haritalar ve planlar, kontrol listeleri, matrisler, ağ diyagramları da kullanılabilir.

Etkileri öngörüldükten ve tanımlandıktan sonra maden projesinin kültürel miras üzerinde yaratacağı etkilerin ne kadar önemli olacağı etkilerin değerlendirilmesi adımıyla belirlenir. Kültür varlıkları üzerindeki olumsuz etkiler ihmal edilebilir olabileceği gibi önemli ancak önleme ve hafifletme tedbirleri ile ortadan kaldırılabılır ya da önemli ancak önlenemez veya hafifletilemez olabilirler.

2.2.5. Hafifletme ve İyileştirme

Kültürel miras varlığı üzerinde maden projesinden kaynaklı olası olumsuz etkiler varsa bunları önleyecek veya azaltacak ve projenin hedeflerine ulaşmasını sağlayacak etki azaltıcı ve etkiyi ortadan kaldıracak “kaçınma” önlemleriyle ilgili alternatifler bu adımda geliştirilir. Koruyucu, hafifletici ve hatta telafi edici olabilirler.

Koruyucu önlemler, kültür varlıkları üzerindeki engellenebilir etkileri ortadan kaldırmaya yöneliktir. Proje planındaki revizyonlar, tampon bölgelerin oluşturulması, görsel etki yönetimleri gibi proje tasarımı esnasında alınabilecek önlemleri kapsayabilir. Hafifletici önlemler ise doğrudan engellenemeyen etkilerin şiddetini veya kapsamını azaltmaya yöneliktir. Kurtarma ve sondaj kazıları, belgeleme ve dijital arşivleme, uygulamalı eğitim ve kapasite geliştirme, izleme çalışmaları ve rastlantısal buluntu prosedürleri hafifletici önlemlerden bazılarıdır.

Telafi edici önlemler ise etkilerin tamamen önlenemediği durumlarda eşdeğer veya daha yüksek kültürel değer yaratmayı hedefler. Yerel kültürel projeler, arkeo parklar ve ziyaretçi alanları, toplumsal hafıza çalışmaları akademik yayın çalışmaları gibi faaliyetler ise telafi edici önlemler arasında sayılabilir.

Hafifletme ve iyileştirme adımıyla önerilen projenin kültürel miras üzerinde yaratabileceği “olumlu” etkiler de tespit edilebilir. Eğer olumlu etkiler varsa, bu etkilerin geliştirilmesi, kültürel mirasın korunması ve sürdürülebilirliği için katkı sağlayabilecek öneriler de bu aşamada ele alınır.

2.2.6. Raporlama

Tüm referans şartları karşılayacak bir KMED raporu proje planlama aşaması sonunda hazır olmalıdır. Rapor KMED sürecinin tüm aşamalarını ve sonuçlarını içermeli ve karar vericiler ile kamu ve paydaşların kullanımına sunulmalıdır. Rapor içerisindeki veriler ve öneriler proje yaşam döngüsünün planlama aşamasından iyileştirme aşamasının sonuna dek kullanılmalıdır. Bu sayede proje yaşam döngüsü boyunca kültürel mirasın korunması ve sürdürülebilir yönetimi için tutarlı, şeffaf ve izlenebilir bir çerçeve sağlanacak, olası olumsuz etkiler en aza indirilerek karar alma süreçlerinin bilimsel, etik ve referans temellerine dayandırılması mümkün olacaktır.

3. İnşaat, İşletme, İşletmeden Çıkarma ve İyileştirme

Proje yaşam döngüsünün planlama aşamasında tamamlanan kültürel mirasın korunmasına yönelik bütçe, süre, ekip ve metodolojik adımlar inşaat, işletme, işletmeden çıkarma ve iyileştirme aşamalarında uygulanır.

İzleme ve denetim adımı kültür varlığı potansiyeli içeren alanlarda, inşaat aşamasından iyileştirme aşamasına dek sürdürülür. İzleme, müdahale edici özelliği ile kültür varlıklarını denetler, tesadüf eseri karşılaşılabilecek kültür varlıklarına karşı ise prosedürlerin işletilmesini sağlar.

KMED, kültür varlıklarını bilimsel tekniklerle kayıt altına alarak gelecek kuşaklara aktarmayı da hedef almalıdır. Bu hedefe ileri seviye metodolojik çalışmalar sonucunda ulaşılır. Maden sahasında yer alan bir arkeolojik varlığın kurtarılması için kurtarma ve sondaj kazıları, kazılardan çıkan kültür varlıklarının taşınması, çizim, rölöve, plan ve haritalama teknikleri, “tarihi çevrenin” modellenerek belgelenmesi ileri seviye metodolojik çalışmalardandır. Bu çalışmalar inşaat ve işletme aşaması ile senkronize sürdürülebilir.

İnşaat ve işletme aşamalarında yürütülen bilimsel saha çalışmalara ait sonuçlar postmining olarak da adlandırılan madencilik sonrası aşamada kitap, kitapçık, e-bülten, makale ve benzeri yayınlarla kamuoyu ile paylaşılmalıdır. Bilimsel bilginin kamuoyu ile paylaşılması sayede kültürel mirasın sürdürülebilirliğine katkı sağlanmış, farkındalık seviyesi yerel, ulusal ve uluslararası ölçekte arttırılmış ve projenin iyi uygulama örnekleri arasında anılması sağlanmış olacaktır.

4. KMED Ekibi ve Profesyonellerin Rolü

Özellikle Avrupa ülkelerinde, kültürel miras etki değerlendirme çalışmaları yalnızca devlet kurumlarıyla (müzeler, enstitüler, koruma kurulları, KUDEB gibi) sınırlı kalmayarak ilgili kamu kurumlarından gerekli yeterlilik belgelerini almış, kültürel mirasa yönelik çalışmalarda onaylı olan özel arkeoloji danışmanlık firmaları tarafından devletin sıkı denetimi altında da yürütülmektedir.

KMED, arkeoloji, mimarlık, antropoloji, jeoloji, coğrafi bilgi sistemleri (CBS) ve koruma bilimleri gibi alanları bir araya getiren çok disiplinli bir yaklaşım gerektiren kapsamlı bir süreçtir. Bu sürecin, ilgili uzmanlık alanlarına hâkim olmayan ekipler tarafından yürütülmesi durumunda; hatalı saha verisi toplanması, mevcut verilerin yanlış veya eksik yorumlanması, bağlamdan bağımsız değerlendirmeler yapılması ve bunun sonucunda kültürel mirasın zarar görmesi gibi ciddi riskler ortaya çıkabilir. Bu tür hatalar, telafisi mümkün olmayan kültürel kayıplara, projelerin durdurulmasına ve önemli itibar risklerine yol açma potansiyeli taşımaktadır.

Uzman ekipler ise yerinde incelemeler, laboratuvar analizleri, arşiv araştırmaları ve CBS temelli yöntemleri bütüncül bir çerçevede kullanarak hem mevcut hem de potansiyel kültürel miras unsurlarını bilimsel doğrulukla tanımlar. Böylece, geliştirilecek etki azaltma ve koruma önlemlerinin bilimsel temellere dayanması ve uluslararası koruma standartları ile uyumlu olması güvence altına alınır.

IAIA (International Association for Impact Assessment) tarafından yayımlanan rehberlerde, kültürel miras etki değerlendirmesinin yalnızca yeterli akademik formasyona ve saha deneyimine sahip profesyonellerce yürütülmesi gerektiği açıkça belirtilir. Birçok ülke mevzuatı ve uluslararası sözleşme KMED süreçlerinde uzman katkısını zorunlu kılar. Örneğin; UNESCO Dünya Kültürel ve Doğal Mirasının Korunması Sözleşmesi (1972) ve ICOMOS’ un Kültürel Miras Etki Değerlendirmesi Rehberi (2022) bunlar arasındadır.

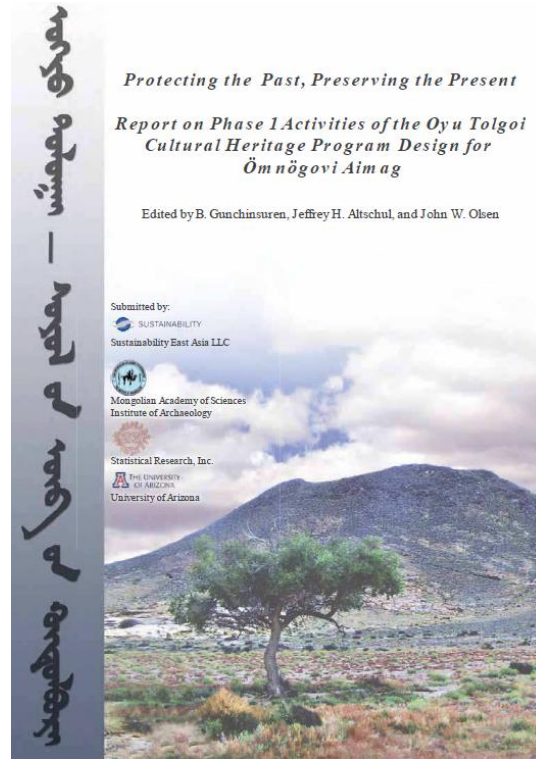
Profesyonel ekipler; yerel ulusal mevzuatlar ile uluslararası koruma ilkelerini eşgüdümlü olarak uygulayarak hukuki riskleri minimize eder. Bu durum, çalışmanın bilimsel geçerliliğinin yanı sıra proje kararlarının güvenilirliğini de artırır. Sonuç olarak KMED’ in uzman ve profesyonel ekiplerce yürütülmesi, metodolojik doğruluk, yasal uyum, risk yönetimi ve toplumsal meşruiyet açısından hayati önem taşır. Bu durum, yalnızca mirasın korunmasını değil, aynı zamanda projenin uzun vadeli sürdürülebilirliğini de güvence altına alır.

5. Uygulama Örnekleri

KMED, madencilik faaliyetlerinin kültürel miras üzerindeki etkilerinin yönetilmesinde belirleyici bir araç olmasına rağmen tek başına yeterli değildir. KMED sonuçlarına uygun tedbirlerin alınması için kaynak sağlanması, bu kaynağın zamanında kullanılması ve süreçlerin yeterlilikleri olan kişiler tarafından yönetilmesi de kültürel mirasın korunması için büyük önem taşımaktadır. KMED sonuçlarına göre tedbirlerin belirlendiği ve uygulandığı projelerde iyi uygulama örnekleri ortaya çıkarken, bazı korumacı tedbirler alınmasına rağmen kültürel mirasın korunmasının önemsiz görülmesi nedeniyle kültür varlıklarının tehdit ve tahrip edildiği kötü uygulama örnekleri ile de karşılaşılabılır.

1873 yılında kurulan, 60.000'den fazla çalışanı ile 35 ülkede madencilik faaliyetlerini devam ettiren ve sürdürülebilirlik politikaları çerçevesinde kendi kültürel miras rehberini de hazırlamış olan İngiltere-Avustralya merkezli çokuluslu, dünyanın en büyük metal ve madencilik şirketlerinden biri olan Rio Tinto kültürel mirasın korunmasında iyi ve kötü uygulama örneklerine farklı projelerde sahip olması bakımından ilgi çekicidir.

Başarılı uygulama örneklerinden Oyu Tolgoi; Moğolistan'ın Umnugovi eyaletindeki, dünyanın bilinen en büyük bakır ve altın yataklarından biridir. Oyu Tolgoi' de Moğol Kültürel Mirasını Korunması Yasası gereği 2009 yılında alana özel bir "Kültürel Miras Programı" hazırlanmıştır. Programın oluşturulmasında arkeoloji, paleontoloji, antropoloji, GIS, restorasyon-konservasyon gibi farklı disiplinlerde görev yapan uzman bir ekip (Moğolistan Uluslararası Miras Ekibi) görev almıştır.



Şekil 4: Oyu Tolgoi Kültürel Miras Programı

Somut ve somut olmayan kültürel mirası kapsayan programın temel amacı kültürel mirası korumaktır ve bu amaçla projeye yönelik bir "Kültürel Miras Yönetim Planı" da oluşturulmuştur.

Planın temel amacı ise projeye ilişkili kültürel miras tehditlerini azaltmak, kültürel değişiklikleri izlemek ve anlamak, kültürel mirasın tanıtımı ve korunması için fırsatları takip etmek, kâr amacı gütmeyen kuruluşları ve halkı teşvik etmek ve desteklemektir. Programla; masa başı ve saha çalışmaları yapılarak erken aşama tespit çalışmaları yürütülmüş, alternatif alan incelemeleri, risk analizleri yapılmış hafifletici ve koruyucu önlemler belirlenmiş ve bu metodolojik adımlarla kültürel mirasın korunması sağlanmıştır. Çalışmanın sonucunda proje alanında hiçbir kültürel miras unsuru zarar görmemiştir. Tespit edilen çok sayıda yeni buluntu sayesinde bölge kültür envanteri önemli ölçüde zenginleşmiştir. Yerel topluluklarla güven ilişkisi geliştirilmiş ve projenin sosyal lisansı güçlendirilmiştir. Gobi coğrafyasının benzersizliğini tarif etmek için Gobi Kültürü adlı bir kavram arkeoloji literatürüne kazandırılmıştır.

Şirketin uluslararası basında da yankı uyandıran ve başarılı bir örnek iken göz ardı etmeler nedeniyle olumsuz sonuçlarla kamuoyunun önüne gelen ve şirketin itibarını zayıflatan örneği ise Juukan Gorge vakasıdır. Batı Avustralya'nın Pilbara bölgesinde 4 demir cevheri madeninin genişletilmesi kapsamında Rio Tinto, çevre politikaları gereği Juukan Gorge'da yer alan kaya sığınakları ve diğer potansiyel kültürel miras alanları için 2003 yılından 2018 yılına kadar çok sayıda etnografik ve arkeolojik yüzey araştırması yaptırmış ve raporlar hazırlatmıştır. Raporlar dışında kazılar ve belgeleme çalışmaları, yerel halk ile istişare süreçleri,

koruma ve kaçınma stratejileri de geliştirilmiş ve yürütülmüş ve ciddi bir kültürel miras yönetim planı (2017-2019) da hazırlanmıştır.



Şekil 5



Şekil 6: Juukan Gorge'da yürütülen kazı çalışmaları (2014)

Ancak şirket yönetimi tarafından saha verilerinin önemsenmemesi, kültürel mirasın değerinin göz ardı edilmesi, yasa ve izin süreçlerindeki boşluklar ile bu boşlukların firma tarafından fırsata çevrilmesi gibi nedenlerle bölgede yaşayan Puutu Kunti Kurrama ve Pinikura (PKKP) Aborjin halkları için kültürel, etnografik ve arkeolojik açıdan ulusal ve uluslararası yüksek öneme sahip 46.000 yıllık iki kaya sığınağı 24.05.2020 tarihinde patlatılarak yok edilmiştir.



Şekil 7: Juukan Gorge, Öncesi ve Sonrası

İyi uygulama örneği olarak başlamışken kötü bir uygulama örneğine dönüşen projenin kültürel miras yönetiminin projeye bazı önemli olumsuz sonuçları olmuştur. Bunların başında hukuki ve yasal sonuçlar gelmektedir. Avustralya Federal Hükümeti tarafından olayla ilgili bir soruşturması başlatılmış şirket ağır

cezalara çarptırılmıştır. Olay, uluslararası medyada geniş yankı uyandırmış ve Rio Tinto'nun çevresel, sosyal ve yönetim (ESG) performansı konusunda uluslararası kınamalarla birlikte küresel çapta büyük bir itibar kaybına yol açmıştır.



Fig. 1: Juukan Gorge Protestları

Şirketin büyük hissedarları, kurumsal yönetimdeki başarısızlıklar nedeniyle ciddi tepki göstermiş, şirketin yönetim kademesinde zorunlu değişiklikler ortaya çıkmış şirketin CEO'su, Demir Cevheri İşletmeleri Yöneticisi ve Kurumsal İlişkiler Direktörü de dahil olmak üzere birçok üst düzey yönetici istifa etmek zorunda kalmıştır. Finansal ve Operasyonel Etki: Şirket, yerel halkla ilişkileri düzeltmek için daha büyük kaynaklar ayırmak zorunda kalmıştır. Skandalın ardından madencilik faaliyetlerinin bir kısmını durdurmak ve operasyonel planlarını gözden geçirmek zorunda kalmış ve projenin zaman takviminde önemli zaman kayıpları ortaya çıkmıştır.

6. Sonuç

Nüfusun hızla arttığı ülkemizde, toplumsal ve ekonomik gereksinimlere paralel olarak maden projeleri de aynı hızla çeşitlenmekte ve genişlemektedir. Türkiye'nin farklı bölgelerinde, özellikle temel hammadde ihtiyaçlarını karşılamak amacıyla gerçekleştirilen madencilik faaliyetleri esnasında kaçınılmaz olarak toprağa ve doğal coğrafyaya müdahale edilmektedir. Toprağa yapılan bu müdahaleler, arkeolojik alanlar, tarihî yapılar gibi tüm kültürel miras unsurları üzerinde olumsuz riskler yaratmaktadır.

Bu riskler; kültürel miras üzerindeki etkilerin uzman bir ekip tarafından detaylı bir şekilde değerlendirilerek raporlanması ve projenin tüm aşamalarında kültürel mirasın dikkate alınmasını sağlayacak planların geliştirilmesi ve bu planların uygulamaya geçirilmesi sayesinde minimize edilebilir.

Ancak ülkemizdeki maden projelerinde gerçekleştirilen kültürel mirasa yönelik bu çalışmalar, genellikle bu projeleri yürüten aktörler tarafından proje önünde önemli bir engel olarak algılanmaktadır. Bu yanlış algının temelinde, ülke genelinde yeterince yerleşmemiş olan kültürel miras bilinci ve etkili bir kültür politikasının olmaması yatmaktadır.

Oysaki; doğru kültürel miras politikasının uygulanması hem kültür varlıklarının korunmasını sağlayan hem de firmaya ekonomik, hukuksal, kurumsal ve sosyal açıdan çok boyutlu artı değerler üreten stratejik bir yaklaşımdır. KMED politikasını doğru izleyen firmalar ulusal mevzuat, uluslararası sözleşmeler ve rehberler ile uyum sağlayarak idari yaptırım, proje durdurma, para cezası veya hukuksal riskleri minimize eder. Ulusal ve uluslararası kamuoyunda ve paydaşlar arasında kültürel mirasa duyarlı, sorumlu bir kurum imajı oluşturup yerel topluluklarla güvene dayalı ilişkiler geliştirilerek sosyal faydanın sürekliliğini sağlar. Olası kültürel miras riskleri erken tespit ederek proje gecikmeleri ve beklenmedik maliyetlerin önüne geçer. Yerel halk, STK'lar, akademik kurumlar ve kamu otoriteleri ile yapıcı iş birliği ortamı yaratarak projeye yönelik olumsuz tepkilerin önüne geçer. Uluslararası finans kuruluşlarının kültürel miras kriterleri karşılayarak şirket performans göstergelerine katkıda bulunur, yatırım ve kredi olanaklarının artırılmasını ve yabancı yatırımcılar nezdinde güvenilirlik sağlanmasını sağlar.

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The impact of legislation on the revival of mining heritage in Slovenia: Discovery of a new mineral resource, the natural pigment ochre

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Abstract

In modern European society, the approach to the complexity of each mine closure is multifaceted, requiring the definition, description, and evaluation of various technical, socio-economic, environmental, and management conditions for each location individually. These conditions are set out in both national and European legislation, which has evolved over time. Currently, legislation is most comprehensively regulated in the field of European coal mine closures within the framework of the Just Transition Mechanism (JTM), an initiative designed to support regions and communities transitioning to a climate-neutral economy while ensuring that no one is left behind. An example of good practice from the Sitarjevec mine in Slovenia prior to the adoption of the JTM is presented in this article. The mine was closed according old mining legislation, but today the degraded area has been revitalised, also with the support of science and art, as a modern approach. Thanks to the EU-supported legislation and funds supporting industrial heritage, economic benefits can also be provided in the heritage site. A new mineral resource, the natural pigment ochre, was discovered in the mine and characterised using electron microscopy, X-ray analysis, and chemical analysis. Preliminary results indicate its potential usefulness in textile dyeing and painting.

Keywords: mining heritage, legislation, revitalization, new programmes

1. Introduction

Mineral resources have played a significant role in the development of human civilisation, to the extent that historical periods are named after them, from the Stone Age, marked by the production of stone tools, to the Bronze and Iron Ages, characterised by advances in metallurgical processes (Erb-Satullo & Klymchuk 2025, Cooper & Grebnev 2023). Although different materials dominated various periods, art remained a common feature of societies, with the oldest examples dating back to cave life, when the first cave paintings were created using natural pigments such as ochre, burnt ochre, and charcoal (Henshilwood et al., 2009). Preserved material remains and works of art provide evidence of the development of human society, while the museums that house them and the caves with cave paintings are exceptional tourist attractions, making a significant contribution to the economy of contemporary society, where it is also crucial to monitor the negative impacts of visitors on the underground space (Alvarez et al., 2010, Habiba Lharti et al., 2025).

Coal holds a special place in mineral resource production and has been an important energy source from the Industrial Revolution in the 19th century to the present day (Jiang et al., 2022). The coal industry has led to the formation of mining communities, which, due to the nature of mining work and the large number of miners and their families, have had a significant sociological impact on society. The comradeship formed deep underground has helped overcome major challenges, such as organising protests to achieve greater social justice.

The most extensive protests, and at the same time the most difficult period for European mining families, occurred in the 1980s in England, when coal mines were closed without adequate solutions for miners

(Gibbon, 1988). Despite attempts to regulate this extremely important economic sector, mining strikes have not abated even in modern times (Harvey, 2016).

The trend of closing coal mines has continued into the 21st century, aiming to achieve climate neutrality by 2050, based on the European Green Deal (URL-1, 2019)

This initiative followed the commitments made by the EU and its member states upon signing the Paris Agreement (The Paris Agreement, 2025). In the coal mining sector, the Just Transition Mechanism was established to support regions requiring greater investment to meet these goals through three areas: 1. People and communities most vulnerable to the transition: facilitating employment opportunities, offering reskilling, improving energy-efficient housing, and combating energy poverty. 2. Companies and sectors in carbon-intensive industries: making the transition to low-carbon technology attractive to investment, providing loans and financial support, and investing in research, innovation, and the creation of new firms. 3. Member states or regions highly dependent on fossil fuels: investing in new green jobs, sustainable public transport, renewable energy, digital connectivity, and clean energy infrastructure (URL-2, 2020).

Slovenia, like many other countries, is aware of its mining history. The topic is particularly relevant in society because, in February 2026, a special law was passed to close the last active mine in Slovenia, the lignite coal mine in Velenje (Uradni list RS št. 12/26, 2026). The closure will be gradual, in accordance with the principles of a just transition for coal regions. Part of the funds will also be allocated to the preservation of mining heritage.

The purpose of the article is to provide an overview of the state of mining industrial heritage through various mining legislation and to highlight opportunities for local communities that have identified new development potential in mining heritage in Slovenia. Although these communities were not included in the modern processes of just transition for coal regions, in some cases this was made possible by previous mining legislation. Mines such as the Idrija mercury mine and the Mežica lead and zinc mine were closed in accordance with the project for the rehabilitation of mining areas, as prescribed by the Mining Act in the 80s and 90s, and the state therefore provided funds for closure (Uradni list SRS, št. 37/87, 1987, Uradni list RS št. 001-22-107/99, 1999). The Idrija mine is now on the UNESCO list of mining heritage and is developing a strong tourist programme within the Idrija Geopark. The Mežica mine has also been integrated into the tourist programme of the cross-border UNESCO Karavanke Geopark, offering a highly attractive experience of the underground environment.

A unique challenge in reviving mining heritage is presented by abandoned mines were at the time, of their abandonment, the regulations had not yet been adapted to modern closure requirements and rehabilitation plans. One such example is the Sitarjevec mine, which over the past ten years has been the focus of a modern tourist programme, driven by the local community's recognition that their mining heritage forms part of their identity. Research and educational institutions are also involved in developing new programmes through projects, contributing their expertise to improve the recognition, preservation, and popularisation of this heritage. Through this cooperation, the Sitarjevec mine's sludge was identified as a natural ochre pigment, suitable for artistic purposes and colour development (Jerčič Jakob et al., 2023, Rant et al., 2021). The development of Sitarjevec mine revival programmes is supported by funding from the local community of Litija, as well as international projects under the INTERREG programme.

All mines abandoned without proper closure projects are now regulated by the Mining Act, Article 100d. This article states that tourist, sports, educational, cultural and other activities may be developed in these areas, creating opportunities for local communities that have not yet participated in the revival of mining heritage due to the previous lack of an appropriate legal basis (Uradni list RS, št. 14/26, 2026).

Each underground mining space is a unique form of underground architecture, shaped by human hands, which is why it represents an invaluable heritage of human development. Mining heritage leaves a mark on industrial heritage, settlement patterns of mining communities, the cultural character of places, including abandonment and degradation, as well as environmentally harmful impacts. Therefore, its effective preservation requires an interdisciplinary approach that recognises the experience of heritage in all its layers, and society must adapt legislation accordingly.

2. Materials and Methods

A sample of sludge (formed by erosion of the abandoned mineralized part of the deposit and subsequently sedimented) was collected from the Sava shaft at the outlet of the Sitarjevec mine. The material was sieved in the laboratory through a 0.063 mm sieve, then air-dried and crushed.

Mineralogical analysis of the pigment was performed using the X-ray Powder Diffraction (XRD) method on an Empyrean PANalytical diffractometer (PANalytical B.V., Almelo, The Netherlands) with Cu K α irradiation ($\lambda = 1.54056 \text{ \AA}$ and graphite monochromator), at 45 kV and a current of 40 mA, over the 2 θ angular range from 4° to 70°, using a step size of 0.01° and a measuring time of 200 seconds per step.

To determine the semi-quantitative analysis of the dry sludge (pigment sample) and the shape of the pigment particles, electron microscopy was performed using a JEOL 5500 LV SEM equipped with Energy Dispersive X-Ray Spectrometry (EDS) in low vacuum mode (between 10 and 15 Pa), at an accelerating voltage of 20 kV and a working distance of 20 mm.

The mine sludge sample from the Sava shaft location was evaluated in accordance with the provisions of Commission Regulation (EU) 1357/2014, Council Regulation (EU) 2017/997, Regulation (EC) No. 1272/2008, the guidelines of the Commission Notice on Technical Guidance on the Classification of Waste (2018/C 124/01), and data from the ECHA dossier (<http://echa.europa.eu/>).

3. Results and Discussion

3.1 The Coal Mine Velenje

After 150 years, the Velenje Coal Mine is ending its operations, as the Act on the Gradual Closure of the Mine has been adopted (Uradni list RS, št. 12/26). This act requires the management of the coal mine and the wider community to cease coal mining by 2045, in accordance with European rules on the green transition. The gradual closure programme envisages two main phases: from 2026 to 2033, when closure works will be carried out alongside remaining production, and from 2034 to 2045, when only closure works will take place. The programme includes technical and technological solutions, a human resources and social package, and an economic and financial framework.

The law permits the technical and safe closure of all 50 kilometres of tunnels and, together with shafts, more than 60 kilometres of underground facilities, thereby preventing future surface risks. Equally important is the social aspect, as the law enables an acceptable transition through natural staff attrition and the option of early retirement, with a strong focus on creating new jobs in the region. Article 4 of the law sets out a more detailed programme for the gradual closure of the coal mine, including mitigation measures for the protection of cultural and technical heritage (both tangible and intangible). This also preserves the programme of the Coal Mining Museum of Slovenia, which has been managed by the Velenje Coal Mine since 1999 (<http://muzej.rlv.si/si/>).

Equally important is the social aspect, as the law allows for a smooth transition with a natural outflow of personnel and the option of early retirement, while strongly emphasising the creation of new jobs in the region.

All programmes for restructuring the Velenje Coal Mine, including those for preserving cultural heritage, are financially evaluated until 2045 and amount to 50 million euros per year.

The Velenje Coal Mine is an example of mine closure coordinated with stakeholders and supported by the Act on the Gradual Closure of Activities, in a manner not previously seen in Slovenia. Therefore, the process requires additional attention from all stakeholders involved in its implementation.

3.2 The Idrija mine and the Mežica mine

The latest post-mining activity programmes at the Idrija mercury mine and the Mežica lead and zinc mine are being carried out as part of the UNESCO Global Geoparks network (<http://www.geopark-idrija.si/si/>, <https://www.geopark-karawanken.at/>). Previously, both mines underwent a closure process in accordance with the mine rehabilitation plan following the cessation of mining activities (Uradni list RS št. 61/10 2010).

The Idrija Mercury Mine is managed by the Mercury Heritage Management Center (CUDHg Idrija), to which the state transferred maintenance in 2016 after the termination of the mining rights of the Mercury Mine Company in Liquidation. After five hundred years of operation, the mercury mine was closed in 1995. The Mercury Heritage Management Center manages its UNESCO heritage, which includes the Antonijev rov tourist mine below the surface and the Hg smelter and compressor station on the surface. The responsibilities of the Mercury Heritage Management Center manager also include monitoring the condition of the mine area, as the town of Idrija is located above the mine shafts. The basic funds for the operation of CUDHg Idrija are provided by the state and are partly co-financed through various domestic and

international projects. It is included in the UNESCO network of global geoparks (<https://www.cudhg-idrija.si/>).

The Mežica mine, with its heritage, is part of the Karawanken UNESCO Global Geopark (<https://www.podzemljepece.com/>). After three hundred years of operation, lead and zinc ore production ceased in 1994, when a mine closure project was prepared in accordance with the Mining Act. The tourist mine and museum have been open to visitors since 1997, and the state provides funds for employees responsible for programme delivery and maintenance. As the heritage of the Mežica mine offered exceptional tourist potential, partly due to its proximity to the Austrian border, it was merged with the neighbouring area in 2015 to form the Karawanken/Karawanken UNESCO Global Geopark. Today, the Mežica mine is known as a destination where visitors can cycle underground, take a train or boat ride, enjoy concerts, or view the museum collection in the mining building on the surface.

3.3 The Sitarjevec mine

The Sitarjevec mine is an example of a mine in Slovenia that was not closed in accordance with the mine rehabilitation project, but was simply deleted from the cadastre of mining areas in 1966 (Herlec et al., 2006). The reason for this was the lack of mining legislation, which allowed mine operators to abandon the activity without adequate measures to ensure the safe abandonment of the activity for both the inhabitants and the environment.

The Sitarjevec mine has the longest history in Slovenia. The first archaeological traces date back to the time of the Celts and Romans, while the first written sources date back to the Middle Ages. The archive written sources show that the mine was closed and reopened several times, depending on which ore body was encountered in the mine and what the market needs were. The Sitarjevec mine is a polymineral ore deposit, where iron, lead, mercury, zinc and, finally, barite ore were mined. Small amounts of silver were also excavated, from which a commemorative lithium tolar was produced at the mint in Vienna (<https://rudniksitarjevec.si/>).

The mine has several entrances through which it was possible to enter freely for a long time, which was especially interesting for mineral collectors, as 60 different types of minerals have been found so far. Amateur researchers of abandoned mines and collectors were also the ones who discovered the fast-growing iron oxide/hydroxide stalactites in the mine and drew the attention of the professional public and the local community of the Municipality of Litija (Jeršek et al., 2018).

The state of Slovenia has declared the Sitarjevec mine a geological natural value of national importance due to its exceptional mineralogical diversity and stalactite structures (Uradni list RS, št. 56/99, 1999).

Legal protection of natural values does not mean that their management is also taken care of in a financial sense, especially when the heritage is linked to mining areas, which require significant investments to ensure safety in underground facilities. Therefore, the further process of revitalization of the mine was taken care of by the local community, which, after several years of efforts and discussions, commissioned the preparation of the Mining Project for the Rehabilitation of the Sitarjevec Mine in 2016, which represented the beginning of the implementation of works with the aim of revitalizing part of the mine for tourist purposes. In 2018, together with project partners, it successfully obtained funds from the INTERREG SI-HR program for the MIEN TOUR project for the first time, and in 2025 from the same program for the second time, for the MINE STORY project. Through various projects, it is revitalizing parts of the mine shafts for tours and developing new tourist programs, including from mine sludge, which has been recognized as a natural ochre pigment.

3.3.1. Mine sludge

The mine sludge is deposited along the mine shafts within the mine and at the outlet of the Sava shaft, as a consequence of natural erosion of the mineralized sections of the mining horizons (Figure 1). Although research has shown that the mine waters inside are markedly acidic, with pH values between 3 and 4, at the outlet of the Sava shaft they are almost neutral, reaching pH values of 7.3 (Miler&Gosar, 2019, EUROFINS d.o.o., 2025).



Figure 1: Discharge of mine water from the Sava tunnel with the disposal of mine sludge

XRD analyses also showed that the mineralogical composition of the mine sludge is goethite (Figure 2). This forms as a result of oxidation processes, in which micro-organisms also participate (Toplak et al., 2021). It is a process of mineralisation of meteoric waters, which flow over sulphide ore bodies along the mine. When sulphides (i.e. FeS_2) are oxidised, oxygen from meteoric water is gradually consumed and mostly soluble sulphides emerge, mainly from soluble Fe^{2+} iron. Water travels down, and when water containing Fe^{2+} enters mine shafts, Fe^{2+} is oxidised to Fe^{3+} due to contact with oxygen from the air. Fe^{3+} is not soluble in water and is first excreted as amorphous ferric oxide hydroxide (ferrihydrite), then partly crystallises as goethite and lepidocrocite (Herlec et al., 2006).

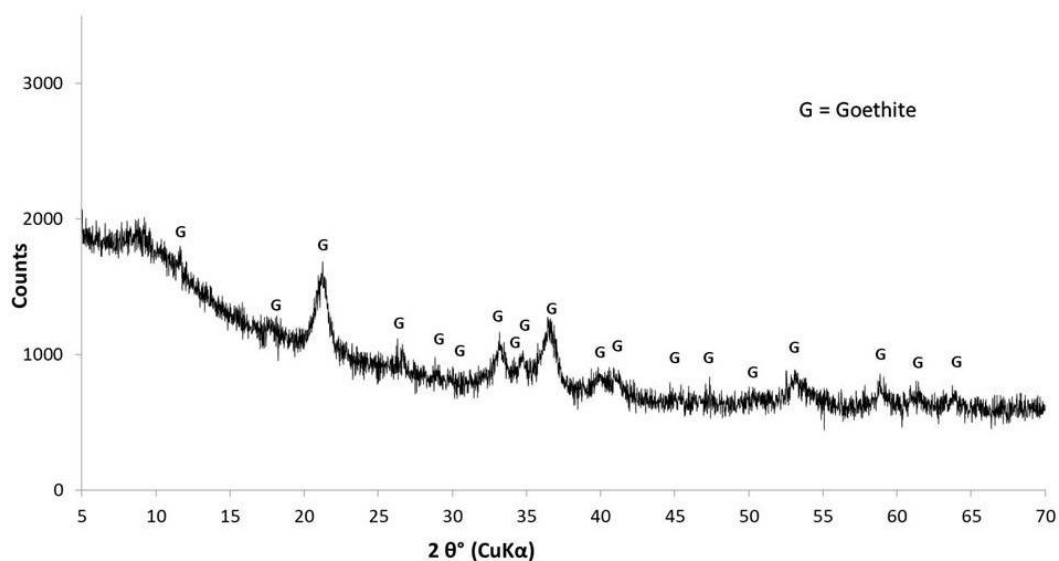


Figure 2: XRD analysis results of mining sludge

Semi-quantitative analysis of dry mine sludge revealed that the particles in the sample are composed of iron with traces of aluminium, silicon, and sulphur, and are round in shape. Their size ranges from nano- to microparticles, which is why the pigment used for developing colours for textile printing was micronised and thus homogenised. For effective colour printing on textiles, it is necessary to ensure that the size of the pigment particles does not exceed 5 μm (Rant et al., 2021). Micronised pigment is also very useful for painting colours, which has been tested and confirmed with various painting techniques (Jerčič Jakob et al., 2023). For the safe use of sludge or natural ochre pigment from the Sitarjevec mine, the chemical analysis of the sample was conducted. (Table 1). The sample contains elevated concentrations of manganese, iron, and zinc, while the concentrations of other metals are below the limit of 0.1%. Iron and zinc in this form are not classified under Regulation (EC) No. 1272/2008, and manganese concentrations do not exceed 25%, which is the limit concentration (Eurofins d.o.o., 2025).

Table 1. Summary of chemical analysis of dry mine sludge from Sava shaft

	Value	Unit	Method
As	74.9	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Al	89.3	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Sb	< 1.0	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Cu	< 10.0	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Ba	143	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Be	< 3.5	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
B	< 35.0	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
TOC	0.77	mg/kg s.s.	SIST EN 13137:2002
Zn	26.086	% s.s	SIST EN ISO 17294-2:2017 modif.
Cd	2.1	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Sn	< 4.0	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Ca	5200	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Mg	< 3.00	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Na	< 3500	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Co	213	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Cr	< 5.0	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Mn	71660	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Mo	< 2.0	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Ni	216	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Se	< 35.0	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Pb	82.2	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Si	28600	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Ta	< 3.5	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
V	< 3.5	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Ti	< 40.0	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Fe	458658	mg/kg s.s.	SIST EN ISO 17294-2:2017 modif.
Hg	0.13	mg/kg s.s.	ISO 16772:2004 brez točke 7.4.2 modif.
S	0.11	mg/kg s.s.	ASTM D 4239(C):1997

4. Conclusion

A historical overview of the abandonment of mining activities in Slovenia, in the context of mining legislation, shows that mine closures have occurred or will occur depending on the applicable legislation and the commitment of local communities to preserving mining heritage.

Post-mining activities therefore vary for different cases of mining heritage in Slovenia, which is also linked to the financial resources invested in new programmes. These are primarily focused on tourism products, as seen in the inclusion of the Idrija and Mežica mines in the UNESCO Geoparks network.

A different process of post-mining activities is underway in the Sitarjevec mine, where part of the mine has been converted into an underground museum. The local community also places great emphasis on new tourism products based on the recognition of the importance of the new natural ochre pigment for this area. For the commercialisation of pigment from the Sitarjevec mine, we recommend developing a brand and securing financial resources to establish a local company to extract and process mine sediment into pigment, thereby adding value to this new mineral resource.

How the heritage will be managed after the abandonment of the Velenje coal mine remains to be seen, but appropriate funds have been allocated for these programmes from the Just Transition Fund, given that the Velenje coal mine has also been managed by the Coal Mine Museum of Slovenia for many years.

Care for degraded environments as part of post-mining activities also includes appropriate monitoring of their condition, which is provided by the managers of these areas and regulated by relevant legislation.

The main concern for the future preservation of mining heritage is the shortage of properly trained personnel in mining, as mine closures also lead to the discontinuation of educational programmes. It is therefore necessary to consider who will be able to maintain the mines in the future and ensure their safe use for tourism and other purposes in accordance with existing legislation. We therefore propose that a dialogue be initiated in Slovenia as soon as possible between policy makers, legislators, former operators, local communities, and research and education organisations on this topic.

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Maden Atık Alanlarının Güneş Enerjisi Üretimine Dönüştürülmesi: Doğu Karadeniz (Gümüşhane) Örneği ve Beklenen Çevresel-Sosyal Kazanımlar

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Özet

Doğu Karadeniz'in zorlu topoğrafyası ve Gümüşhane'nin dağlık yapısı, bölgeye enerji erişimini güçleştirmekte ve şebeke kayıplarını artırmaktadır. Onay sürecini tamamlayan bu proje, halihazırda imalat ve arazi düzenleme aşamasındadır. Maden Atık Alanları Rehabilitasyon Programı kapsamında kapatılan atık alanları, sıfır arazi israfı ilkesiyle yenilenebilir enerji sahalarına dönüştürülmektedir. Çevresel rehabilitasyon odaklı yaklaşımla, atık alanları geoteknik stabilizasyon, sızdırmaz kaplama ve yeniden tesviye çalışmalarıyla çevresel risklerden arındırılmaktadır. Maden geçmişinin neden olduğu toprak kirliliği ve su kaynağı tehditleri bertaraf edilerek alanlar ekosistem sağlığı açısından güvenli hale getirilmektedir. Hiçbir ek arazi kullanımı yapılmadan, tahribatlı alanlar PV dizi yerleşimi, inverter, SCADA entegrasyonu ve performans izleme altyapısıyla modern bir enerji tesisine dönüştürülmektedir. Projenin tamamlanmasıyla birlikte; bölgesel arz güvenliğinin güçlenmesi, şebeke esnekliğinin artması, iletim kayıplarının azalması ve enerji erişim eşitsizliğinin giderilmesi hedeflenmektedir. Temiz enerji üretimiyle bölgenin karbon ayak izinin azaltılması, Türkiye'nin iklim hedeflerine yerel ölçekte katkı sağlanması ve istihdam oluşturulmasıyla sosyo-ekonomik refahın desteklenmesi beklenmektedir. Bu girişim, benzer coğrafyalara ilham verecek ölçeklenebilir bir sürdürülebilirlik modeli sunmaktadır.

Anahtar Kelimeler; Maden atık alanı rehabilitasyonu, Güneş enerjisi, Yenilenebilir enerji

English Title of the Paper

Abstract

The challenging topography of the Eastern Black Sea region and the mountainous terrain of Gümüşhane make energy access difficult and increase grid losses. This project, which has completed the approval process, is currently in the manufacturing and land preparation phase. Waste areas closed under the Mine Waste Area Rehabilitation Program are being converted into renewable energy sites based on the principle of zero land waste. With an approach focused on environmental rehabilitation, waste areas are being cleared of environmental risks through geotechnical stabilization, impermeable lining, and re-grading works. Soil contamination and water source threats caused by mining history are being eliminated, making the areas safe in terms of ecosystem health. Without any additional land use, degraded areas are transformed into modern energy facilities with PV array installation, inverters, SCADA integration, and performance monitoring infrastructure. Upon completion of the project, the objectives are to strengthen regional supply security, increase grid flexibility, reduce transmission losses, and eliminate energy access inequalities. Clean energy production is expected to reduce the region's carbon footprint, contribute to

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Turkey's climate goals at the local level, and support socio-economic prosperity by creating jobs. This initiative offers a scalable sustainability model that will inspire similar regions.

Keywords; Mine waste area rehabilitation, Solar energy, Renewable energy

1. Giriş

Artan küresel enerji talebi ve iklim değişikliğiyle mücadele gerekliliği doğrultusunda, yenilenebilir enerji kaynaklarına yönelik yönelim dünya genelinde ivme kazanmıştır. Özellikle uluslararası iklim değişikliği sözleşmeleri kapsamında sera gazı emisyonlarının azaltılmasına yönelik hedefler, alternatif ve düşük karbonlu enerji sistemlerine olan ilgiyi artırmaktadır. Bununla birlikte, enerji arz güvenliğinin sağlanması ve konvansiyonel enerji üretim teknolojilerinin çevresel etkilerinin minimize edilmesi gerekliliği, enerji sektöründe yapısal bir dönüşümü zorunlu kılmaktadır. Bu kapsamda, sürdürülebilirlik ilkeleri doğrultusunda tasarlanan, maliyet etkin ve çevresel açıdan güvenli yenilenebilir enerji teknolojileri araştırma ve geliştirme çalışmalarının odağında yer almakta; söz konusu teknolojiler farklı endüstriyel alanlarda giderek daha yaygın bir şekilde uygulanmaktadır (Chiras ,2010& Cichon ,2012). Bu bağlamda güneş enerjisi, temiz, yenilenebilir ve yüksek ölçeklenebilirlik potansiyeline sahip olması nedeniyle madencilik sektöründe öne çıkan alternatif enerji kaynaklarından biri olarak değerlendirilmektedir.

Fotovoltaik (PV) sistemlerin, ABD'deki Goldstrike madeni (Steel Market Europe ,2014), Şili'deki Chuquicamata madeni (Nielsen ,2011& Beetz ,2012), Weipa madeni (Australian Renewable Energy Agency ,2016), Avustralya'daki DeGrussa madeni (McCrae MA ,2015), Güney Afrika'daki Thaba madeni (Global Climate Partnership Fund ,2016) ve Surinam'daki Rosebel madeni (Colthorpe A. Canadian company to build 5MW PV plant at Suriname gold mine ,2013) gibi aktif maden sahalarında başarıyla uygulandığı rapor edilmiştir. Bununla birlikte, ABD'deki Chevron Questa madeni (Chevron ,2015), Almanya'daki Meuro madeni (Cichon ,2012) ve Kanada'daki Sullivan madeni (CBC News ,2014) gibi terk edilmiş maden alanlarında da PV sistem kurulumlarının gerçekleştirildiği görülmektedir. Bu uygulamalar, maden kapanışı sonrasında atıl durumda kalan sahaların yeniden işlevlendirilmesi ve alternatif ekonomik faaliyetlerin geliştirilmesi açısından önemli bir dönüşüm modeli sunmaktadır.

Ancak mevcut çalışmaların büyük ölçüde uygulama örneklerinin tanımlanması ve enerji üretim performansının değerlendirilmesiyle sınırlı kaldığı; maden sahalarının jeoteknik, çevresel ve uzun dönemli arazi kullanım planlaması bağlamında bütüncül bir değerlendirme çerçevesinin yeterince ele alınmadığı görülmektedir. Özellikle maden atık depolama alanlarının veya kapatılmış sahaların yenilenebilir enerji altyapısına entegrasyonu konusunda sistematik tasarım kriterleri ve sürdürülebilirlik analizleri literatürde sınırlı düzeydedir. Bu durum, söz konusu alanların enerji üretim potansiyeli ile çevresel rehabilitasyon süreçlerinin entegre biçimde ele alınmasını gerektirmektedir.

1.2. Madencilik faaliyetlerinde entegre edilen fotovoltaik enerji sistemleri

1.2.1 Faaliyeti sonlandırılmış maden alanlarında fotovoltaik enerji sistemlerinin entegrasyonu

1.2.1.1. Kanada, Sullivan madeni, 2 MW fotovoltaik sistem

Sullivan madeni, Kanada'nın Britanya Kolombiyası eyaletinde, Kimberley kentinde konumlanmaktadır. Söz konusu maden işletmesinde, zengin cevher rezervlerine ulaşmak amacıyla açılan çok sayıda kuyu ve yeraltı galerisi aracılığıyla 140 milyon tonun üzerinde kurşun ve çinko cevheri ile pasa malzemesi çıkarılmıştır. Madenin faaliyetlerinin sonlandırılmasının ardından, Teck Cominco (güncel adıyla Teck Resources) tarafından sahanın rehabilitasyonu amacıyla beş yıllık bir süreçte yaklaşık 70 milyon Kanada doları tutarında yatırım gerçekleştirilmiştir. Ayrıca şirket, saha kaynaklı drenaj sularının izlenmesi ve arıtılması çalışmalarını sürdürmeye devam etmektedir.

Ontario'nun batı kesimindeki en büyük güneş enerjisi tesisi olma özelliğini taşıyan Sullivan madeni üzerinde kurulan fotovoltaik (PV) enerji santralinin inşası, Kimberley, Britanya Kolombiyası'nda bulunan kontamine bir maden sahasının yeniden değerlendirilmesini amaçlayan 5,3 milyon Kanada doları bütçeli bir proje kapsamında 2014 yılında resmen başlatılmıştır. Rocky Dağları'na hâkim bir sırt üzerinde konumlanan bu tesis, Batı Kanada'daki ilk ticari ölçekli güneş enerjisi santrali, eski bir maden sahası üzerinde kurulan ilk

güneş enerjisi uygulaması ve aynı zamanda BC Hydro elektrik şebekesine entegre edilen ilk büyük ölçekli güneş enerjisi tesisi olma niteliğini taşımaktadır.

1.2.2. Aktif maden işletmelerinde fotovoltaik (PV) sistemlerin entegrasyonu

1.2.2.1. Şili, Chuquicamata Madeni'nde Fotovoltaik sistem (1 MW)

Chuquicamata madeninin elektrik ihtiyacını karşılamak amacıyla 1 MW kurulu güce sahip bir güneş enerjisi santrali (Calama Solar 3) yaklaşık 62.500 m²'lik bir alan üzerinde tesis edilmiştir (Şekil 1). Söz konusu tesiste toplam 4.080 adet düzlemsel fotovoltaik (PV) modül kullanılmış olup, modül dizileri tek eksenli güneş takip sistemleri aracılığıyla otomatik olarak yönlendirilmektedir. Yıllık yaklaşık 2.500 kWh/m² düzeyindeki küresel güneş ışınımı değeri ile Atacama Çölü, dünya genelinde en yüksek güneşlenme potansiyeline sahip bölgeler arasında yer almaktadır. Bu yüksek güneş ışınımı koşullarının sağladığı avantaj sayesinde, Chuquicamata maden sahasında kurulu PV sistemi 2011 yılından itibaren yıllık ortalama 2,69 GWh düzeyinde elektrik üretimi gerçekleştirmektedir (Nielsen ,2011).

Chuquicamata madeninin enerji gereksinimini karşılamak üzere 1 MW kurulu güce sahip Calama Solar 3 güneş enerjisi santrali, yaklaşık 62.500 m² büyüklüğündeki bir sahada kurulmuştur (Şekil 1). Tesis kapsamında 4.080 adet düz yüzeyli fotovoltaik (PV) modül kullanılmış olup, modül grupları tek eksenli güneş izleme mekanizmaları aracılığıyla otomatik biçimde konumlandırılmaktadır. Yıllık yaklaşık 2.500 kWh/m² seviyesindeki küresel yatay ışınım değeri ile Atacama Çölü, küresel ölçekte en yüksek güneş enerjisi potansiyeline sahip bölgeler arasında kabul edilmektedir. Bu elverişli radyasyon koşullarının etkisiyle, söz konusu PV sistemi 2011 yılından bu yana yıllık ortalama 2,69 GWh elektrik üretim kapasitesine ulaşmıştır (Beetz ,2012).



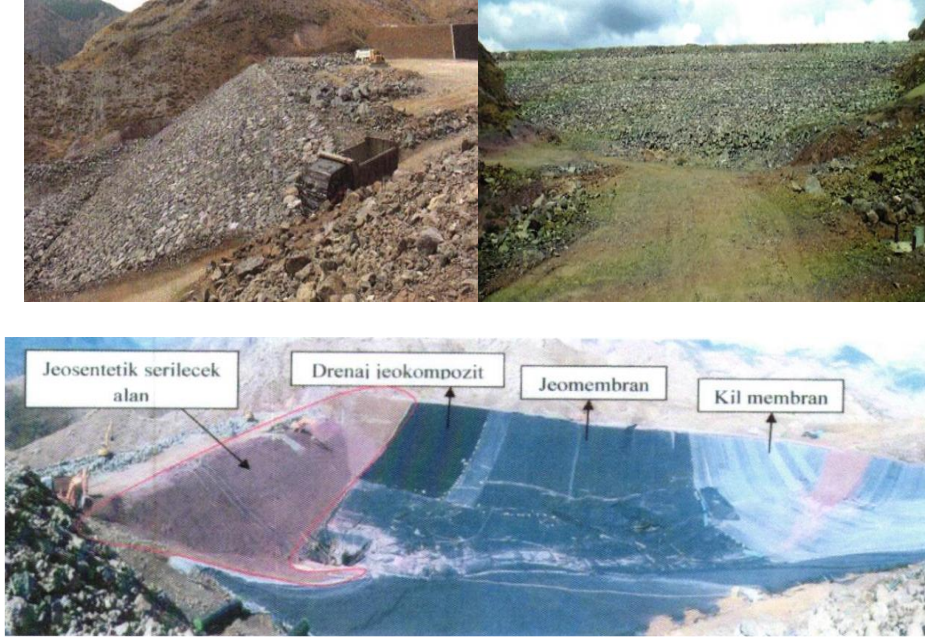
Şekil 1: Şili, Chuquicamata Madeni yakınlarındaki Calama Solar 3 enerji tesisinin havadan görünümü (görüntü kaynağı: Bing Maps, <http://www.bing.com/maps>).

2. Materyal ve Yöntem

2.1 Çalışma alanının tanımı

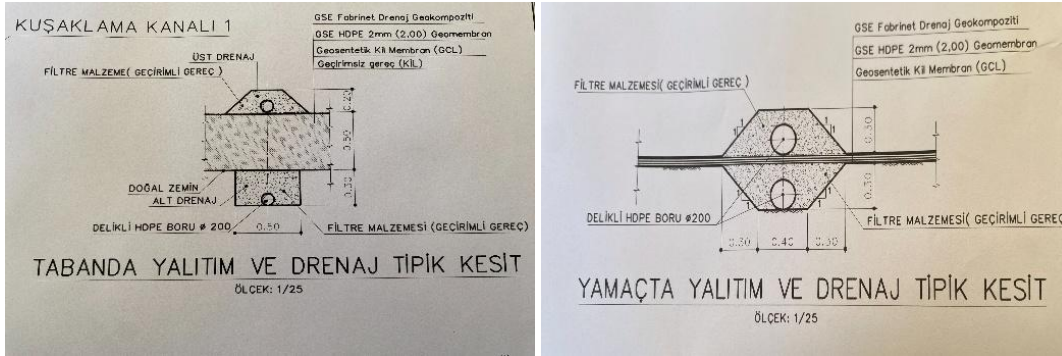
ADT 1 sahası, Eosen yaşlı andezit ve bazalt ile bu birimlere ait piroklastik kayalardan oluşan Alibaba Formasyonu üzerinde konumlanmaktadır. ADT 1 alanı ve yakın çevresinde hâkim litolojiyi, genellikle gri ve siyahımsı-gri tonlarda gözlenen andezitik ve bazaltik karakterdeki volkanik kayalar oluşturmaktadır. Yoğun çatlak sistemleri içeren ve büyük ölçüde ayrışma göstermiş olan bu volkanitlerde; yaygın silisleşme, koyu yeşil renk ile karakterize edilen kloritleşme ve çatlak zonları boyunca gelişmiş kalsit damarları sıklıkla izlenmektedir (Alemdağ& Sarı ,2025).

ADT 1 gövdesi kaya dolgudan inşa edilmiş bir atık barajıdır. ADT 1 depo alanının zemin düzenlenmesinden sonra drenaj ve taban geçirimsizlik sistemleri yapılmıştır. Depolama alanı üç ayrı kademe inşa edilmiştir. Birinci kademe 1388-1407 kotları arası ikinci kademe 1407-1422 kotları arası, üçüncü kademe 1422-1423 kotları arasındadır.



Şekil 2: Gövde kaya dolgu ve kaplama malzemeleri

Drenaj sistemleri: Periyodik su seviyesi artışlarına karşı, geçirimsizlik tabakası altına delikli boru ve çakıl filtreli bir alt drenaj sistemi planlanmıştır. Bu amaçla delikli HDPE drenaj boruları ve çakıl filtreler kullanılmıştır.



Şekil 3: Tabanda ve yamaçta drenaj kesitleri



Şekil 4: Kaplama işlemleri tamamlanmış ve aktif şekilde kullanılmış olan ADT

2.2 ADT alanının rehabilitasyonu

Tesis kapsamında yer alan ADT 1, işletme ömrünü 2018 yılı içerisinde tamamlamış olup, Gümüştaş Madencilik ve Tic. A.Ş.'ye ait atık depolama barajı kapatma projesi doğrultusunda rehabilitasyon sürecine alınmıştır. Bu kapsamda, proje sahasında gerçekleştirilecek düzenleme kazı ve dolgu çalışmaları sonucunda nihai atık üst kotunun 1423,86 m seviyesine getirilmesi planlanmaktadır. Atık yüzeyinde oluşabilecek yüzey akışlarının kontrollü biçimde uzaklaştırılabilmesi amacıyla, üst kot seviyesinden sedde/kret yönüne doğru %1 eğim verilerek drenaj sağlanacaktır. Oluşacak yüzey suları, sedde/kret boyunca inşa edilecek yüzey suyu drenaj kanalı&kanalları aracılığıyla toplanacaktır.



Şekil 5: ADT-1 Alanından ADT-2(Sulu Atık) Alanı Görünümü ve Tahliye Borusu

Depo üst örtüsü teşkilinde sırasıyla;

- Min. 50 cm Toprak/Tampon Tabakası
- Geosentetik Kil Tabakası (GCL)
- Geokompozit Drenaj Tabakası
- Min. 50 cm Bitkisel Toprak Tabakası/ Tampon tabakası şeklinde olacaktır.



Şekil 6: Rehabilitasyon çalışmaları yapılmaya başlanan ADT-1 alanı kapatma aşamalarına dair fotoğraflar

Tampon tabaka: Sülfürlü atıkların oksijen ve su ile temasını sınırlayan; genellikle alkali karakterli veya düşük geçirgenlikli malzemelerden oluşan ara örtü katmanıdır. Çalışma sahasımızda tampon tabaka olarak 50 cm kalınlıklı doğal kazı toprağı uygulanmıştır.

Geosentetik Kil Tabakası (GCL): Su ile temas ettiğinde şişerek çok düşük hidrolik iletkenliğe ulaşan bentonit kil içeren, sıvı ve gaz geçişini sınırlandırmak amacıyla kullanılan ince tabakalı sentetik bariyer sistemdir. Çalışma sahasımızda Geomas marka geosentetik kil tabakası kullanılacaktır. GCL serimi yapılırken şekilde görüldüğü gibi birleşim bölgelerine 35-40 cm'lik bentonit kil serpilir amaç ise bentonit su alıp şişerek bu bölgelerdeki geçirimsizliği daha güvenli hale getirir.

Geokompozit Drenaj Tabakası: Suyun kontrollü şekilde toplanması ve uzaklaştırılması amacıyla tasarlanmış kompozit malzemedir. Çalışma sahasımızda Geomas marka geokompozit drenaj tabakası kullanılacaktır.



Şekil 7: Tampon tabaka, GCL ve geokompozit drenaj tabakası uygulaması (Kürtünlüoğlu ,2025)

2.3 Güneş Enerjisi Santrali

ADT-1 sahasında gerçekleştirilen rehabilitasyon çalışmaları sonrasında planlanan güneş enerjisi santrali (GES) projesinin, madencilik sektöründe benzer atık depolama alanlarının yeniden işlevlendirilmesine yönelik örnek bir uygulama modeli oluşturacağı öngörülmektedir. Atık depolama sahasının rehabilitasyonunun ardından hayata geçirilecek GES yatırımı sayesinde, söz konusu alanın atıl durumdan çıkarılarak ekonomik değere dönüştürülmesi mümkün olacaktır. Bunun yanı sıra proje, yenilenebilir enerji üretimi yoluyla karbon ayak izinin azaltılmasına katkı sağlayacak çevresel bir kazanım niteliği de taşımaktadır.

Çalışma kapsamında, fotovoltaiik panellerden oluşan bir güneş enerjisi sistemi tasarlanmış olup, sistem yerleşimi saha topoğrafyası, nihai yüzey geometrisi ve kapatma tasarım kriterleri dikkate alınarak planlanmıştır.

Güneş enerjisi sisteminin tasarım sürecinde, atık depolama barajına ilişkin kapatma kriterleri temel tasarım kısıtı olarak dikkate alınmıştır. Taşıyıcı konstrüksiyonun belirlenmesinde, yüzey müdahalesini en aza indirecek ve kapatma örtü sisteminin bütünlüğünü zedelemeyecek çözümler öncelikli olarak değerlendirilmiştir. Ayrıca, sistemden kaynaklanacak yapısal yüklerin atık kütlesi üzerindeki etkileri analiz edilmiş; panel yerleşim planı ise yüzey drenajının sürekliliği ve genel şev stabilitesi koşulları gözetilerek oluşturulmuştur.

Güneş enerjisi sistemi taşıyıcı konstrüksiyonunda, yüksek dayanım-düşük ağırlık optimizasyonu sağlamak amacıyla S355 kalite soğuk şekillendirilmiş yapısal çelik tercih edilmiştir. Bu malzeme, daha ince kesitlerle yeterli moment ve kesme kapasitesi sağlayarak sistem toplam ağırlığını azaltmaktadır.

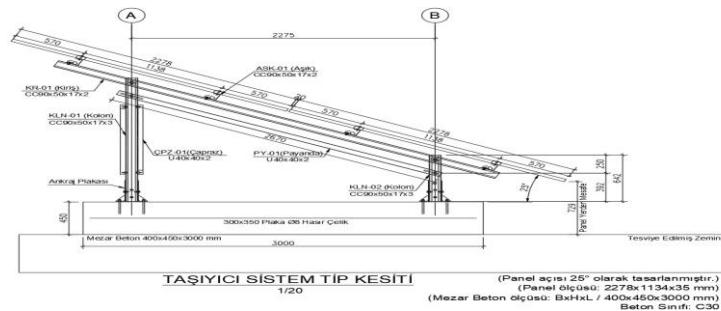
Çelik Sınıfı (S355 Cold Formed)

- Minimum akma gerilmesi (f_y) : 3619,99 kg/cm²
- Minimum kopma gerilmesi (f_u) : 5200,55 kg/cm²
- Elastisite modülü (E): 2141404 kg/cm²
- Termal Faktör (A) : 0,00001 C

Tablo 1: Zemin Değerleri

Deprem Bölgesi	S _s /S ₁	I	R _x	R _y	Zemin
DD-2	0,433/0,152	1,5	4	4	ZC

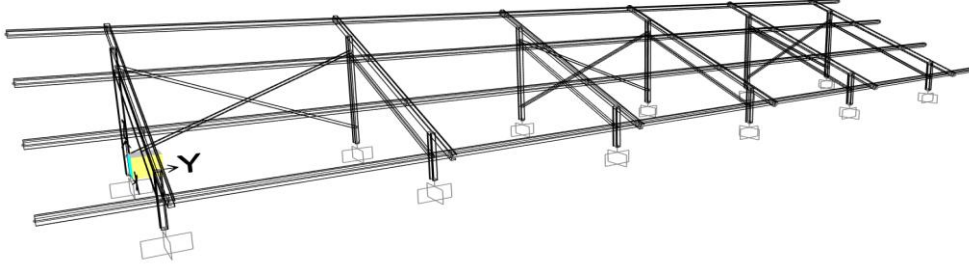
2.3.1. Taşıyıcı sistem



Şekil 8: Taşıyıcı Sistem Rakam Aksı Kesiti

2.3.2. Modelde Kullanılan Kesitlerin Detayları

2.3.2.1. Model 3D Görünüşü



Şekil 9: Kesitlerin 3D Gösterimi

3. Bulgular ve Tartışma



Şekil 10: Panellerin yerleşimi

Tablo 2: Panellere ait mekanik özellikler (*Montaj şekline bağlı olarak kablo uzunluğu değişebilir).

Panel Ölçüleri	2278 mmx1134 mmx35 mm
Hücre	TOPCon M10
Hücre Sayısı	144 yarım hücre
Ağırlık	31 kg ±1 kg
Ön/Arka Cam	2 mm, yüksek geçirgenlik ve düşük demir oranına sahip temperlenmiş cam
Çerçeve	Eloksal kaplamalı alüminyum
Bağlantı Kutusu	Koruma sınıfı IP68 (3 bypass diyotlu)
Kablo	4 mm ² solar kablo, Uzunluk: 400 mm (+),300 mm (-) **

Tablo 3: Evirici Özellikler

Giriş (DC)	
Maksimum giriş gerilimi	1500 V
MPPT sayısı	16
MPPT gerilim aralığı	500 V-1500 V
Minimum start çalışma gerilimi	550 V
Maksimum giriş MPPT kısa devre akımı	60 A
Çıkış (AC)	
Maksimum AC güç	352 KVA
Nominal AC gerilimi	800 V
Maksimum çıkış akımı	254 A
Anma şebeke frekansı	50/60 Hz

4. Sonuçlar

Bu çalışma, Doğu Karadeniz gibi enerji erişiminin zor olduğu, madeni atıkların sürdürülebilir sürdürülebilir güneş enerjisi (GES) üretimine dönüştürülmesini incelemektedir. Mevcut klasörlerdeki kapatma örtüsü tipi, yüzey drenajı ve drenaj düzeninin GES sistemindeki bölmelerin rol oynadığı kanıtlanmıştır. Yüzeyin bütünlüğünü korumak adına, ortadan kaldırmak mutlaka tercih edilmelidir. "Sıfır arazi israfı" ilkesiyle kritik avantajlar sunmaktadır.

GES'e ait sisteme ilave yüklerin kritik bir olumsuzluk oluşmadığı tespit edilmiştir. Ancak atık malzemesinin zamana bağlı deformasyonu ve uzun dönem oturması muhafazakâr seçimi ve etkin performans izleme programlarının sınıflandırılabilir. Bu sayede, ek arazi kullanımı ol modern enerji tesislerine dönüştürülmektedir. Bu bütünlük yaklaşım, yapı hayati önem vermek.

Atık baraj sahalarının enerji üretimi amacıyla yeniden kullanılabilir hale getirilmesi, arazi kullanımının muazzam ölçüde genişletilmesi ve endüstriyel olarak sürdürülebilirliğe muazzam katkı sağlar. Tarım ve yerleşim alanlarıyla rekabeti azaltan bu uygulamalar bir yazma yeteneği sunuyor. Projenin kesilmesiyle; bölgesel arz güvenliği güçlenecek, şebekeleştirilecek, dağıtım kayı dramatik şekilde azalacak, Türkiye'nin iklimlendirilmiş *Güçlü bir yerel katkı sağlanacak ve istihdamla sosyo-ekonomik refah etkin bir şekilde desteklenecektir.

Sonuç olarak, atık depolama kapasitesi güneş enerjisinin bütünüyle hem ekonomik hem de riskleri tamamen ortadan kaldıran, geniş sosyo-ekonomik faydalar sunan, uygulanabilir ve alternatif bir arazi kullanımınıdır. Bu çalışma, benzer coğrafyalara ilham verecek, ölçeklenebilir ve sürdürülebilir bir model olarak öne çıkıyor.

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