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Review

Transitional and Post-Mining Land Uses: A Global Review of Regulatory Frameworks, Decision-Making Criteria, and Methods

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Abstract: Post-mining land management is an integral part of surface mining and quarrying operations. In this context, the questions raised concern what course of action is mandated by laws and regulations; what type of land reclamation should be implemented, taking into account the site-specific conditions prevailing in each mining area; what are the appropriate land uses; and by what criteria and methodology can these be determined? The literature review conducted as part of the present study revealed that in addition to the traditional 4R actions of land management, namely remediation, restoration, reclamation, and rehabilitation, two more actions, repurposing and co-purposing, have now been added, with the purpose to address the social and economic impacts of mine closures. Furthermore, numerous land uses were documented and categorized into 11 classes, 38 sub-classes, and 119 alternatives. Nine criteria for selecting land uses were identified, expressed through 72 attributes that served as input information for 22 multicriteria methods, which, in most cases, were applied in combination of two or more.

Keywords: abandoned mines; mine closure; land rehabilitation; social impacts mitigation; economic growth; regional development

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1. Introduction

Surface mining of mineral resources is used when minerals are close to the earth's surface. This technique removes the soil (topsoil or fertile soil) and rock formations above the mineral deposit, causing significant changes in morphology and land use. It is estimated that more than two-thirds of the world's annual mineral production is extracted by surface mining. The global market for surface mining was estimated at USD 38.5 billion in 2020 and is expected to grow at an average growth rate of 3.2% this decade, reaching USD 54.18 billion by the end of 2031 [1].

The most common types of surface mining are open-pit mining, quarrying, strip mining, contour (strip) mining, and mountaintop removal mining, each with specific variations depending on the minerals extracted and the equipment used for excavation and haulage (Table 1) [2–4]. No matter the method, the advantages of surface mining include lower costs and better safety compared to underground mining. The disadvantages concern the occupation of land for many decades, and risks to human health and the environment, mainly due to soil and water pollution and dust emissions.

Surface mining is practiced in many countries, causing numerous social, economic, and environmental impacts. In addition, in many mines and quarries, ore processing and utilization are carried out on-site, causing effects through the operation of processing or beneficiation plants, power plants, and associated infrastructure. Additional pollution sources are mechanical equipment and other infrastructure to support mining operations, transportation networks, such as belt conveyors and railroads, heavy vehicles, workshops, staff facilities, administration buildings, and other infrastructure [5,6].

Table 1. Surface mining methods.

Methods	Attributes	Deposits
Open-pit mining (or open-cast or area mining)	Removal of overburden to create access to the deposit, use of conventional digging and hauling equipment or continuous mining systems, dumping of overburden both inside and outside the mining area.	Large, near-surface deposits of metals, industrial minerals, and coal.
Quarrying	Similar to open-pit but with vertical faces and steep slopes.	Dimension stones and aggregates.
Strip mining	Long excavations in the direction of the mine face advance, relatively constant overburden thickness.	Horizontally bedded and relatively thin deposits, usually coal.
Contour (strip) mining	Progressive excavation of the slope of a hill until the stripping ratio reaches its marginal value.	Deposits located in mountainous areas.
Mountaintop removal mining	Removal of the top of a hill, dumping of overburden in waste embankment outside the mining area.	Deposits located in mountainous areas.

The mines and quarries closure automatically puts the regions concerned into a transitional period. It is a phase of change and transformation for the natural and man-made environment, as well as a turning point for all stakeholders involved. How this phase is carried out is decisive for a safe and sustainable future. Mining companies are obliged to take a series of measures related to the decommissioning of infrastructure and the restoration of the land affected by mining works in order to contribute to a smooth transformation of the local economy and society. Although mining companies are usually focused on mine closure activities necessary to satisfy the criteria listed in the environmental permit and relinquish any residual liabilities, many stakeholders require interventions that with potential to create favorable conditions for developing new economic, environmental, and social activities.

Land reclamation in the surface mining industry, though a relatively new development, has significantly evolved since its inception. Prior to the 1960s, post-closure land management of mines and quarries was rarely followed by environmental restoration actions from either companies or governments. Abandoned mines and quarries were often left with no removal of the fixed and mobile equipment, without necessary soil and water decontamination, and without restoration of the land to its former state or, at least, rehabilitation according to contemporary techniques that support the development of new activities. During the 1970s and 1980s, the increasing concern regarding environmental issues of mine and quarry closures (e.g., acid drainage, decontamination, and land reclamation), alongside broader sustainable economic, environmental, and social considerations, prompted governments to enforce stricter regulatory controls on mine closure processes. The legal framework was further amended in the 1990s to regulate issues relevant to the costs of abandoned mine and quarry remediation and reclamation, effectively transferring the financial burden from taxpayers to mining companies. Nowadays, remediation is considered an integral, continuous process throughout the entire operating period of a surface mine. Therefore, mining companies must prepare detailed environmental management plans that incorporate the latest environmental protection technologies [7].

Regarding alternative post-mining land management options, Table 2 presents seven commonly employed strategies in mine closure projects. These strategies can be applied simultaneously within the same project, depending on factors such as land acreage, site-specific environmental and social parameters, and associated costs. Furthermore, the selected strategies must be closely related to the intended land uses. The ultimate selection of land uses for a specific mine closure project is influenced by several factors, including policy priorities, available budget, and the unique characteristics of the area [8].

Table 2. Post-mining land management strategies.

Land Management Strategies	Targets	Main Characteristics
Abandonment	None	"Zero action", changes in the disturbed land occur only due to slow-evolving natural process
Remediation	Soil, water	Physical, chemical, or biological decontamination of soil and water
Restoration	Ecosystem	Improvement of degraded areas in order to return the ecosystem to its previous state
Reclamation	Land	Development of a new ecosystem, similar to the previous one, which fulfills the same functions
Rehabilitation	Land	Application of new land uses that support sustainable environmental and social development
Repurposing	Site	Development of alternative uses for pre-existing infrastructure
Co-purposing	Site	Coexistence of mining with other activities developed in areas that are no longer used for mining operations

A few decades ago, the abandonment of mines and quarries, including their buildings, associated infrastructure, and networks, was the most common response by mining companies after ceasing operations. These companies were not required to prepare plans to mitigate the impact on the landscape and the natural and social environment. Essentially, their responsibility ended with the cessation of mining activities, with no obligation to restore the affected land. Consequently, they did not take steps to prevent potential degradation of the area [9]. This "zero action" approach led to widespread abandonment, causing severe environmental problems in regions with intensive mining activities. The resultant environmental and social pressures prompted the introduction of relevant legal regulations. In most countries, obtaining a mining license now requires submitting a plan for the management and restoration of the land [10].

In the transition or post-closure phase of mining, the impacts on air, water, and soil quality have a high priority. If it is determined that the mine area may pose a risk to human health and nature in the short or long term, *remediation* measures are implemented first and foremost [11]. Remediation is the process of correcting a particular problem, reversing or ending its impact on the environment. Remediation involves decontaminating the area, especially the soil, using physical, chemical, and biological methods [9]. Then, it is assessed whether it is possible to return the landscape to its former state. The process of *restoration* involves the large-scale improvement of degraded areas to restore the ecological balance and the original biodiversity of the ecosystem, in terms of function and structure, as it existed before. In many cases, decontamination of the soil is not required and restoration procedures begin immediately [12]. However, when ecosystem restoration is not possible, land *reclamation* is considered. Reclamation is usually appropriate for derelict and abandoned areas where it is not possible to restore the original ecosystem to its previous state, but another state suitable for the area is established. In this case, the ecosystem is essentially replaced by other species that fulfill the same function [13]. Yet, there are also cases of mines and quarries where the above measures cannot be applied and the conditions essentially result in a forced change of traditional land uses to new, stable, permanent, and beneficial land uses, leading to an overall *rehabilitation* of the area. Although the new land uses are not related to the previous ones, they contribute to the environmental, social, and economic enhancement of the area.

In addition to the above strategies, which are related to the overall management of the mining areas, it is worth noting that the mining infrastructures, such as ore processing plants, water reservoirs and pumping stations, stockyards, workshops, buildings, and roads, are not removed, demolished, or recycled, but can be used for a new purpose. *Repurposing* can help to ease the transition of the local economy and mitigate the impact of mine closure by using the existing infrastructure in a way that makes it an element of the area's development [14,15]. Finally, there is always a possibility of coexistence of similar activities. *Co-purposing* concerns the development of a new activity in the mine and quarry area that is not competitive to mining operations or mine land management works, so that the transition period will be smooth, beneficial, and with a development perspective [14].

Following a description of the methodology employed in this literature review in Section 2, the main part of this article, is organized as follows: Section 3 addresses the legal framework, summarizing current national legislation for mine land management and reclamation in different countries. Section 4 briefly overviews land-use classes and alternative land uses after mine and quarry closures. It presents recent literature on the classification of land uses, detailing a wide range of options, commonly identified classes of land uses, and alternative land use options within each class, along with their areas of application. Sections 5 and 6 outline, respectively, the selection criteria for post-quarry and post-mining land uses identified in the literature review, and an overview of the multi-criteria methods for land-use selection. Finally, Section 7 provides the discussion and conclusion of the paper.

2. Materials and Methods

The present literature review focuses on the issue of developing new land uses during the transition period and after the definitive closure of open-pit mines and quarries. Four main themes were examined:

- The current legislative framework.
- Alternative land uses.
- Criteria for selecting land uses.
- Decision-making methods for choosing the most appropriate land uses.

The analysis is based on 90 articles identified through Google Scholar or the authors' contacts on ResearchGate. It should be noted that multiple searches using different sets of keywords were required to identify articles related to post-mining land uses in surface mines, as searches using all keywords simultaneously returned minimal results and did not identify significant articles.

As a first step, we searched for articles published during the last five years in order to obtain a view of the recent developments of the topic under investigation. As land reclamation has been systematically elaborated on a global scale since the 1970s, our research was further extended in sources (articles, legislation, global organizations) from the 1970s and onwards. The aim was to find typical examples of mining and quarrying land reclamation and to examine the relevant processes in those countries where mining is essential for the national economy.

The articles were then categorized based on the four directions mentioned above, their geographical distribution, and their year of publication. Statistical analyses were avoided due to access restrictions to specific databases and publishers with which the University of Western Macedonia does not collaborate.

3. Selected Legal Regulations from Various National Contexts

Comprehensive reviews of the evolution of the legal frameworks for mine closure and land reclamations are provided by Clark and Clark [16] and Ignatyeva et al. [17]. The first law for the restoration of disturbed land was adopted in the United States (West Virginia, 1939), while, one year later, Germany passed directives for the restoration of open spaces caused by open-cast mining. The main requirements for restoration were the conservation of soil cover, disposal or neutralization of toxic waste, elimination of the disturbed mining areas, and restoration of the original terrain and vegetation. However, prior to 1985, the issue of mine closure had been of a low priority for most countries, as evidenced by the large number of abandoned mines that exist. Only a few countries had in place a mineral policy and legislation that provided for land reclamation.

Nowadays, most scholars agree that comprehensive mine closure and land reclamation legislation must include the following basic components: specific provisions for land reclamation and rehabilitation; requirements of Environmental and Social Impact Assessments, as well as work plans for mitigating these impacts; an effective bonding system that ensures the finance of land reclamation works; special provisions for abandoned mine site management; and specific monitoring and enforcement procedures to ensure compliance. The research conducted by Clark and Clark [16] showed that most of the developed countries and many developing countries in Asia, Africa, and South America, such as Bhutan, Bolivia, Mongolia, and the Philippines, have policies and laws that follow the guidelines mentioned above. Nevertheless, many of the world's largest mining countries have inadequate land reclamation policies and legislation, and only a few provide a framework for sustainable development of post-mining land uses. In addition, all mining countries have a major problem with the land reclamation of abandoned mines and try to develop an appropriate and cost-effective action plan for dealing with the issue.

In the European Union, significant progress regarding site rehabilitation and after-care followed the introduction of the Extractive Waste Directive 2006/21/EC. This directive establishes minimum requirements, procedures, and guidelines aimed at preventing or minimizing adverse environmental effects and associated human health risks from the management of extractive waste. It mandates that the competent authority requires a financial guarantee before the commencement of any operations involving the accumulation of extractive waste. Consequently, mine operators are obligated to develop an Extractive Waste Management Plan, which must encompass a closure plan, including site rehabilitation. The implementation of this directive is further regulated by various decisions concerning technical guidelines for establishing financial guarantees, waste facilities classification criteria, waste characterization, the definition of inert waste, and technical guidelines for inspections [18,19].

Examining the legal aspects of specific land reclamation issues, it is worth highlighting the role of bonds in ensuring that the reclamation of the mined area will be completed. According to Cheng and Skousen [20], there are seven important factors for a successful reclamation bonding system: laws and regulations, administrative authority, bond types, bond size, calculation method, bond release, and public participation. The same scholars consider that the United States has a mature and unified reclamation bonding system, which, despite controversies and problems that still exist, has been proven highly successful in helping companies be responsible for reclamation liabilities. More than 80% of the land disturbed since 1977 has been reclaimed.

Moreover, Shelestukov et al. [21], Verchagina et al. [22], and Nurhiman [23] discussed the problem of criminal liability and sanctions for mining business actors who do not carry out land reclamation as stipulated in the relevant laws and regulations, either on purpose or due to errors in the implemented methods and techniques, or as a result of illegal mining activities. Shelestukov et al. [21] proposed also that criminal and administrative penalties and other amounts of compensation must be transferred to the funds used for the payment of technical documentation and the reclamation of the illegally mined lands.

Finally, the laws and regulations that are in force in the USA, Australia, Canada, Germany, and the Republic of South Africa concerning the mitigation of environmental impacts related to acid mine drainage were presented by Jacobs and Testa [24].

The following paragraphs and Table 3 present, briefly, the legal frameworks for mine land reclamation of selected countries. It should be noted that the attempt to review the legal framework encountered several difficulties, primarily because laws and regulations are issued in each state's official language and often not available in English. Nevertheless, efforts were made to gather data from countries across all continents through publications in scientific journals in English, with the risk that the list of legal documents presented may not be complete and up to date.

Republic of South Africa: The first laws relevant to coal mine rehabilitation in the Republic of South Africa appeared around 1991, when mines had to carry out detailed environmental impact assessments and have environmental management programs in place before the start of mining activities. It is worth noting that mine closures before 1956 were not subject to legislative closure requirements and are now the responsibility of the State [8].

Australia: The Australian state governments are responsible for rehabilitation laws and supervising most mining operations within their jurisdictions. The national government of Australia is responsible for matters of national importance, such as those falling within the scope of the Environmental Biodiversity Protection and Conservation Act (1999). The legal dimension of environmental issues related to mining operations is defined in the Mining Acts and Environmental Protection Acts of Australian states. According to these Acts, any proposal for a mining project that has the potential to have significant impacts on the environment must be notified to the Environmental Protection Authority. This Authority evaluates the proposal and draws up a report on whether the proposal should go ahead. Regarding mineral extraction and the environment, four important aspects are always taken into account: (i) evaluation and recommendations on environmental management, (ii) cooperation between the mining industry and community on environmental management, (iii) compliance with environmental terms during mining operations, and (iv) cooperation with other government organizations to preserve areas under special protection and not to exclude land from the development of other land uses. In 2011, the Cabinet of Mineral and Petroleum Resources (MCMPR) and the Minerals Council of Australia (MCA) tabled the "Strategic Framework for the Management of Abandoned Mines in the Mineral Industry" [25]. It is worth noting that a separate mining regeneration fund has been set up in Tasmania.

Brazil: Since 1988, the Brazilian constitution has highlighted the obligation of governmental agencies to preserve and restore ecological processes and the diversity of ecosystems for present and future generations [26]. It orders the rehabilitation of degraded areas by the originator and constitutes penalties in the case of infringement. To preserve, enhance, and rehabilitate environmental quality, the Brazilian National Environmental Act (Law 6938/1981) authorizes the National Environmental Council (CONAMA) as the advisory and deliberative body for national environmental policies. The council develops licensing standards for impacts and decides on fines and penalties. The executive bodies forecasted in the National Environmental Act are the Brazilian Institute for Environment and Natural Renewable Resources (IBAMA) and the Chico Mendes Institute for Conservation of Biodiversity, which is responsible for mining activities within conservation units. Both institutions develop activities to control the use and exploitation of natural resources and grant environmental licenses for mining and other enterprises [27].

Table 3. Principal laws that regulate mine land reclamation and post-mining land uses in various countries.

Country	Law	References
Republic of South Africa	Minerals Act (Act 50, 1991); Mineral and Petroleum Resources Development Act (Act 28, 2002)	[11,24]
Australia	Mining Act (1978); Environmental Protection and Biodiversity Conservation Act (1999); Environmental Protection Acts and Regulations of Australian states (e.g., Queensland's Mineral and Energy Resources (Financial Provisioning) Act (2018)), Strong and Sustainable Resource Communities (SSRC) Act (2017), and Environmental Protection (Rehabilitation Reform) Amendment Regulation (2019)	[16,20,24,25]
Brazil	Constitution of Brazil; Decree-Law No. 227/1967; National Environmental Act (Law 6938/1981); Decree No. 9, 406/2018	[26,27]
Canada	Canadian Environmental Assessment Act (CEAA, 2012); Provincial Laws and Regulations (e.g., Ontario's Mining Act, 1990, and Quebec's Regulation respecting mineral substances other than petroleum, natural gas, and brine, 1988).	[16,20,24,28–30]
China	Land Administration Law (revised, 1999); Land Management Act (1999); Land Reclamation Regulation No. 592 (2011); Regulation on Compiling Land Reclamation Plan (2011); Implementation Measures on Land Reclamation Regulation (2012); Completion Standards on Land Reclamation Quality (2013). Other legislation of the People's Republic of China relevant to mine land reclamation: Mineral Resources Law (1986, amended in 1996 and 2009), Environmental Protection Law (revised, 2014); the Coal Law (1996); Water Resources Law (2002); Water and Soil Conservation Law (2010); Forestry Law (2019); Grassland Law (2021)	[16,20,22,31,32]
France	Mining Code (Law 94-588, 1994); Environmental Code (1999)	[33]
Germany	Federal Mining Act (1982, revised in 2006)	[16,17,24]
Greece	Regulation of Mining and Quarrying Works (Ministerial Decision 2223, Official Gazette of the Government 1227-14/06/2011)	[34]
India	Mineral Concession Rules (1960); Mineral Conservation and Development Rules (1988); Mine Closure Rules MCDR (2017)	[16,35,36]
Indonesia	Indonesian Constitution (Article 33); Law No. 40/2007 on Social and Environmental Responsibility of Companies of Limited Liabilities (Article 74); Law No. 4/2009 on Mineral and Coal Mining (Article 96); Government Regulation No.78/2010 on Post-Mining Reclamation; Minister of Energy and Mineral Resources Regulations No. 7/2014 on the Implementation of Reclamation in Mineral and Coal Mining Business Activities	[16,23,37–41]
Iran	The Consitution of the Islamic Republic of Iran (Article 45); Mining Act (1938, last amended in 2011); Forests Nationalization Act (1962); Environmental Protection and Improvement Act (1974); Environmental Regulation for Mining Activities 14/2005	[16,42]
Poland	Resolution No. 256 (1961); Resolution No. 301 on the Reclamation and Redevelopment of Land Transformed (1966); Protection of Agricultural and Forest Land Act (1971, revised in 1995); Geological and Mining Law (1994)	[43,44]
Turkey	Regulation on the Recovery of Land Degraded as a Result of Mining Activities (2010)	[45]
UK	Coal Mines Regulation Act (1908); Mining Industry Act (1920); Coal Act (1938); The Town and Country Planning Act (Scotland, 1947); Coal Industry Act (1949); Mineral Workings Act; Mines and Quarries Act (1969); Opencast Coal Act (1958); Mines Act (North Ireland, 1969); Environmental Protection Act (1990); Coal Industry Act (1994); Environment Act (1995)	[16,17]
USA	National Environmental Policy Act (NEPA, 1970); Surface Mining Control and Reclamation Act (SMCRA, 1977)	[17,20,22,24,46]

Canada: Every Canadian provincial government has the power to enact laws related to property, contracts, natural resources, employment, land use, planning, education, and healthcare. The federal government has overlapping jurisdiction in several areas, such as taxation and the environment. In this context, mining activities are governed by the laws of the province or territory. The Canadian Environmental Assessment Act (CEAA-2012) is the basic legislative framework for all environmental impact assessment procedures required when the mining project is proposed. In general, a federal environmental assessment is necessary for most projects. The government has the right to require a public hearing to accept or reject a proposed mining project.

China: The Chinese government set regulations for the rehabilitation of the mining areas in 1988, defining rehabilitation as the activities aimed at restoring the original ecosystem destroyed by the mining process, preventing subsidence, and reusing land. The revised Land Management Act (1999) stipulates that all users should be responsible for the rehabilitation of the land attributable to mining, subsidence, and waste generated following the relevant national legislation. On 5 March 2011, the State Council issued and implemented Land Reclamation Regulation (LRR) No.592. LRR includes six chapters and 44 articles. Compared with the regulations issued in 1988, the main differences can be summarized by the following aspects: the comprehensive definition of the reclamation object, provisions for damaged land by production and construction activities and natural disasters, clarification of the main responsibility of the land reclamation, enhancement of the land reclamation obligations constraint mechanism, strengthening of the land reclamation incentive mechanism, and clarification of the institutional responsibility. Based on LRR, the Regulation on Compiling Land Reclamation Plan (RCLRP), the Implementation Measures on Land Reclamation Regulation (IMLRR), and Completion Standards on Land Reclamation Quality (CSLRQ) were also issued in 2011, 2012, and 2013, respectively [31,32].

France: The French Mining Code (code minier) was passed in the early 19th century. This old Mining Code was amended by Law No. 94-588 in 1994, which organizes existing jurisprudence and sets goals for better protection of the environment. It can be considered as a redefinition to harmonize the French Mining Code according to the relevant European regulations. The Environmental Code (Code de l'Environnement), in turn, introduced in 1999, aimed for a more coherent regime by the government. The code addresses many environmental issues, including liability clauses [33].

Germany: The first German mining law dates back to 1865. Amendments to the law on mining reclamation were enacted in 1929. Due to the increase in demand for coal after World War II, mine reclamation works were suspended. However, in the early 1950s, restoration efforts were on the rise and laws were enacted with a more detailed description of requirements (Knabe, 1964). The legal framework was amended several times until it was replaced in 1982 by the Federal Mining Act, which was revised in 2006, including requirements for scheduling mine closure and land rehabilitation.

Greece: The mineral deposits exploration, the mines and quarries exploitation, the processing of mineral raw materials, and the environmental restoration are governed by the Regulation of Mining and Quarrying Works [34]. The Regulation lays down rules for the rational deposit exploitation, safety, and health of the workers and local communities, and environmental protection Article 90 refers to the special environmental protection and land restoration measures; in particular, in paragraphs (b) any surface excavation must be carried out with steps of appropriate geometric characteristics, to create the least possible aesthetic alteration of the landscape and to ensure its restoration in stages and as a whole; (g) the final form of the reclaimed land must be in harmony with the natural characteristics of the wider area and, in the case of public or municipal or community land, provision must be made to meet the local needs for special land uses, following the instructions of the Regional and Local Government; and (h) the reclamation of the mine benches should be carried out gradually and its destruction is not allowed after the end of the project.

India: The existence of a plan for refilling the final mine pit with extracted rock volumes and the restoration of the mine land is a prerequisite to starting mining activities. However, the economics of many mines in India can only support limited remedial actions, with refilling the final pit with excavated materials reduced or abandoned entirely [35,36].

Indonesia: The Indonesian Constitution (Article 33, paragraph 3) declares that the earth, water, and natural resources contained therein are controlled by the state and used for the greatest prosperity of the people. In this context, Law No. 40/2007 concerning companies of limited liability states, in Article 74, that a company carrying out business activities related to natural resources is obliged to implement Social and Environmental Responsibility [37]. Moreover, the mining companies must complete mining reclamation works, which are regulated by Law No. 4/2009 about Mineral and Coal Mining (Article 96). These interventions are described in detail in the Governmental Regulations Number 78/2010 about Post-Mining Reclamation, and the Minister of Energy and Mineral Resources Regulations No. 7/2014 about the Implementation of Reclamation in Mineral and Coal Mining Business Activities [38–41].

Iran: Despite the old history of mining in Iran, legal documents discussed it for the first time in 1908, and the first mining-specific act was temporarily ratified in 1917 and became a Mining Act in 1938. Since then, the Mining Act has been amended several times up to 2011. The Constitution of the Islamic Republic of Iran addresses the public assets in Article 45, which preserves the right of public assets and property, such as mineral deposits. These shall be at the disposal of the Islamic government for it to utilize in accordance with the public interest. The cabinet ratified the environmental regulations for mining activities 14/2005 based on Article 35 of the Mining Act of 1998. This enactment contains very important points concerning environmental protection that represent the deeply perceived importance of the environment and the change from mere exploitation of nature to optimum, reasonable, and responsible productivity. Additional provisions for mining activities are included in the Forests Nationalization Act (1962), which states that the Iranian Forestry Organization is responsible for the protection, revival, and development of lands and buildings of all forests, rangelands, and natural woodlands, and the exploitation of these areas, as well as in the Environmental Protection and Improvement Act (1974), which states that the issuance of any license for mine exploration and exploitation for regions that have been determined as national parks, wildlife habitats, and protected areas is subject to the approval of the Supreme Council of Environment [42].

Poland: In Poland, the first legal act imposing the obligation to reclaim and redevelop lands that had undergone devastation was Resolution 256 of the Economic Committee of the Council of Ministers on 12 July 1961 [43]. Later, legal acts concerning the reclamation and development of agricultural land were the Resolutions of 1966. For the first time, many terms related to land reclamation appeared in these Resolutions that concerned activities of the extractive industry, mainly opencast mining. The Act of 26 October 1971, on the protection of agricultural and forest land, added new principles of land reclamation and development covering the entire national economy. Mining activities are also subject to the provisions of the Geological and Mining Law, which introduced the obligation requiring reclamation and redevelopment of land after mining activities. The land reclamation provisions included in the Act of 3 February 1995 are also relevant to the protection of agricultural and forest land [44].

Turkey: The Regulation on Reclamation of Lands Disturbed by Mining Activities (2010) is an important milestone for post-closure planning and aims to regulate basic mine rehabilitation processes [45].

UK: The main laws related to mining and the environment are: the Coal Mines Regulation Act (1908), Mining Industry Act (1920), Coal Act (1938), Town and Country Planning Act (Scotland, 1947), Coal Industry Act (1949), Mineral Workings Act, Mines and Quarries Act (1969), Opencast Coal Act (1958), Mines Act (North Ireland, 1969), and Environmental Protection Act (1990). Concerning coal mining, the central governing body is the Coal Authority, which was established under the Coal Industry Act (1994) during the privatization of the industry. The Environmental Protection Act was amended by the Environment Act in 1995, setting out a detailed framework for the mandatory remedial actions for soil contamination.

USA: The establishment of the Soil Conservation Service in the early 1930s, and increasing local and state concerns about land degradation due to surface mining, made the protection of land resources an important public issue after World War I. This movement evolved into opencast mining legislation, firstly in West Virginia in 1938, and then in Indiana (1941), Illinois (1943), Pennsylvania (1945), and Ohio (1947). The National Environmental Policy Act (NEPA) was signed in 1970. The range of activities covered by NEPA is quite diverse, including decision-making for permits. As part of the implementation of NEPA, the Presidential Council for Environmental Quality (CEQ) was created to monitor the implementation of NEPA. CEQ's responsibilities include ensuring that federal agencies comply with NEPA requirements, overseeing the federal Environmental Protection Agency (EPA) over the environmental impact assessment process implementation, and issuing regulations and other guidelines for federal agencies regarding compliance with NEPA [22]. Today, the reclamation and mitigation of environmental impacts of mining activities carried out on public and private lands in the US are regulated by federal or state laws and mainly the Surface Mining Control and Reclamation Act (SMCRA 1977) [46]. This law sets federal standards and provides guidelines and regulatory processes, which have led to significant changes in both mining practices and restoration techniques. Before the entry into force of this law, the United States had accumulated more than 46,000 unliquidated mines and more than 85,000 abandoned without reclamation mines and quarries. Since the adoption of SMCRA, the Office of Surface Mining Reclamation and Environment (OSMRE) has closed more than 43,000 abandoned mines and mine shafts, removed more than 950 miles of dangerous sides coal mines and more than 3700 hazardous water bodies, and eliminated more than 129,000 acres of hazardous embankments.

4. Transitional and Post-Closure Land Uses

The literature review has shown that a diverse range of land use options have been pursued following the closure of surface mines and quarries. Table 4 presents the land uses implemented globally to date. These land uses were categorized based on twelve general classes, as proposed by [6,8,14,47–49]. However, in the subsequent analysis, only eleven classes are discussed, as no documented cases of post-mining land-use development in tundra regions were found.

Figure 1 illustrates the distribution of the 38 land-use sub-classes and 119 alternative land uses, identified in the present literature review as having been implemented following the cessation of mining activities and the completion of environmental reclamation efforts, across the 11 land-use classes.

Based on the above data, it is evident that a greater variety of land uses is found in the class of residential and commercial use. This can be attributed to the need to meet multiple stakeholders' demands while also utilizing an area's unique characteristics and the infrastructure left behind by mining activities.

Land uses related to industry are comparatively fewer in both number and type. However, in recent years, there has been a gradual shift towards locating renewable energy units, particularly photovoltaic parks, within decommissioned mines.

Agricultural and livestock land uses are widespread in many countries, including the United States, as they provide the opportunity to reintegrate large, reclaimed areas into the productive potential of a region. These land uses satisfy a significant portion of stakeholders when there is a traditional engagement with agriculture and livestock in an area.

The creation of wildlife refuges or wetlands requires that the broader area of the surface mine intervention possesses the characteristics necessary for wildlife habitation. Given that mining activities are often located far from urban areas, meeting this requirement is usually not difficult.

Land uses involving plantings and forest creation in rehabilitated areas are perhaps the most widespread. This is due to several factors: (a) the legislative and regulatory framework of many countries governing mine land rehabilitation mandates plantings, even in areas where forests did not exist before mining, and (b) plantings serve the mining companies, as the required technology is readily available from subcontractors and the cost is acceptable. Additionally, the water within the rehabilitation area, usually collected in the remaining mine pit, can be utilized for coexisting with adjacent forested areas and recreational spaces.

Table 4. Land-use classification.

Land-Use Classes	Land-Use Sub-Classes	Alternative Post-Mining Land Uses Implemented Globally to Date	References
Urban or residential areas	Residential areas	Single- and multiple-family housing, mobile home parks, or other residential lodgings.	[6,15,48,50–55]
	Commercial uses and services	Retail or trade of goods or services, hotels, motels, stores, restaurants, other commercial establishments, houseboats, churches, military installations, fire training arenas, shopping malls, exhibition centers, open-air shops, cafes, swimming pools, and libraries.	
	Public facilities and public use	Temporary homeless shelters, mobile homeless sanitation units, convention centers, mobile citizen service units, citizen service areas, and social service buildings.	
	Educational facilities	National monuments, world cultural heritage sites, sports facilities, astronomical observatories, botanical gardens.	
	Recreation and sports	Multi-use recreation park, including mountain bike trails, road bike tracks, cross country running tracks, scuba diving centers, ice rinks, concert venues, equestrian trails and picnic facilities, organized camping areas, museums, casinos, ski resorts, golf courses, ski slopes, motorsports, artificial ski centers, paragliding centers, geological natural monuments, zoos, ecotourism centers.	[6,15,25,26,48–55]
	Transportation, utilities, network Infrastructures	Roads, railway lines, water supply networks, wastewater treatment plants.	[6,48–51,53,56,57]
Industrial areas	Industries, heavy and light manufacturing facilities, production of materials for fabrication and storage of products	Industrial development incubators, industrial facilities, warehouses—logistics, trade centers, brick factories, organic vegetable processing plants.	[6,48,50,51]
	Energy Production	Wind power plants, wind power systems.	[51,58,59]
		Solar Power Plants (SPP)	[15,53,58–60]
		Biomass-fired heat and power plants	[15,61]
		WtE (Waste-to-Energy) plants	[14,62]

Table 4. *Cont.*

Land-Use Classes	Land-Use Sub-Classes	Alternative Post-Mining Land Uses Implemented Globally to Date	References
Agriculture	Cropland	Barley, wheat, chickpeas	[3,49,63]
	Energy crops	Sorghum, artichoke	
	Other agricultural activities	Orchards, groves, vineyards, nurseries, cocoa trees, greenhouses, and ornamental horticultural areas.	
	Recreational and educational activities	Agrotourism, multifunctional farms.	
Livestock farms	Pastureland, rangeland	Herbaceous rangeland, shrub and brush rangeland, clumps of bushes.	[49,50]
	Poultry farms	Breeding units	[49]
Wildlife	Wildlife shelters	Orangutans, bears, wolves, hares, wild cats, deer, reindeer, coyotes, foxes, opossums, raccoons, etc.	[49,56,64]
	Wildlife sanctuary		
Forestry / Forest land	Deciduous forests	Reforested areas (e.g., maple, oak, beech, elm, poplar, birch, eucalyptus), collection of natural forest products (e.g., gum, cork, resins, balsam, kapok, acorns, horse chestnuts, mosses, lichens, mushrooms, herbs).	[3,9,15,20,34,47,52,57,63,65,66]
	Evergreen forests	Reforested areas (e.g., pine, fir, cypress, cedar), collection of natural forest products (e.g., gum, cork, resins, balsam, kapok, acorns, horse chestnuts, mosses, lichens, mushrooms, herbs).	
	Mixed forests	(As the above two sub-groups)	
	Plantations and nurseries	Aesthetic plantations, plantations for logging and timber production, nurseries	
Aquatic areas	Water bodies: streams, canals, lakes, reservoirs, bays	Water treatment, water storage, irrigation, fire protection, flood control and water supply, artificial reefs, artificial lakes	[6,11,15,49,57,67]
	Aquaculture	Nila fish, Mujair fish and others, catfish, goldfish, tilapia, bluegill, largemouth bass, crappie, and channel catfish.	[6,49,56,67]
	Recreational and sports	Water bikes, rowing boats, development of nautical activities, diving facilities, marina (ports), organized camping area,	[15,34,48,49]
	Energy storage	Hybrid Pumped Hydro Storage, Renewable Energy Source (RES) projects	[59]

Table 4. *Cont.*

Land-Use Classes	Land-Use Sub-Classes	Alternative Post-Mining Land Uses Implemented Globally to Date	References
Wetlands	Forest wetlands	Wildlife (aquatic and/or amphibian), recreational fishing.	[47,56,67]
	Non-forest wetlands	Wildlife (aquatic and/or amphibian), recreational fishing.	
Barren land Waste lands	Mine pits	Natural restoration of the environment, spontaneous vegetation of grasses and trees. (Common land uses for all sub-groups)	[9,50,68,69]
	Overburden dumps		
	Dry tailings		
	Quarries and gravel pits		
Remining	Raw Material	Co, Zn, Au, other precious metals	[70–72]
	Recovery of secondary material	Tantalum and Niobium	[72]
Waste disposal sites	Landfill sites	Legal landfill, illegal landfill	[20,43–45,48,56,64,73–75]
	Waste treatment units	Waste treatment units	[62]
	Solid waste management facilities	Construction and demolition waste units Material storage facilities: scrap metal, tires, wooden train track sleepers, conveyor belts Waste material utilization facilities: tire sculpture, building, construction, garden fencing, furniture, auditoriums, horse and cow bedding, windbreaks, animal feeders, industrial yards, geotextile, waste rock facilities	[6,48,64]

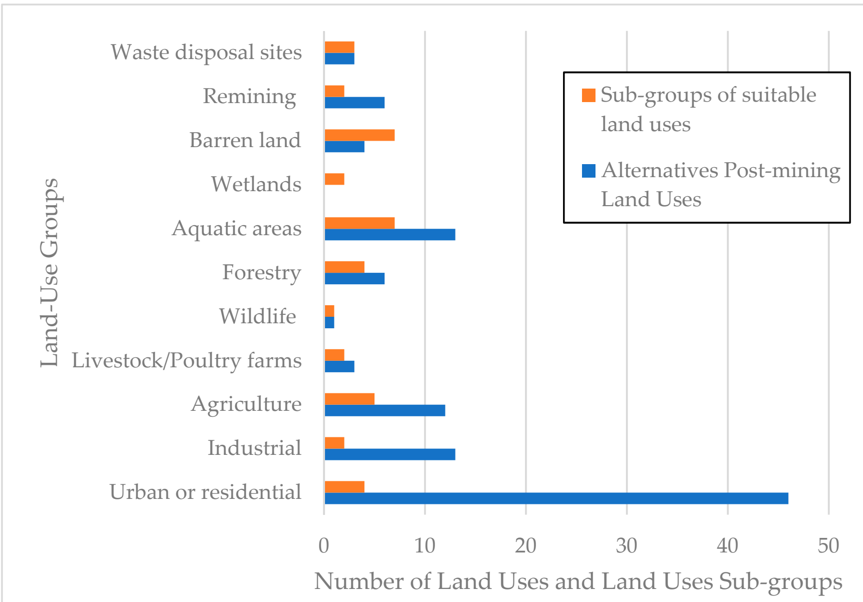

Figure 1. Number of land-use sub-groups and land uses for each of the eleven post-mining land-use groups.

The existence of barren lands after the closure of a surface mine remains a strong possibility even today. This is particularly true in countries where the legal framework does not compel mining companies to allocate the necessary funds for land rehabilitation. In these cases, changes in land morphology, flora, and fauna occur naturally and very slowly. At least the risk of invasive species entering the ecosystem, mainly associated with human interventions, is reduced.

The shortage of sufficient quantities of mineral raw materials at reasonable prices poses a risk to digital transformation and the energy transition. Therefore, the possibility of producing primary raw materials or recovering secondary materials from mines and waste deposits should not be overlooked. For this reason, before developing new land uses, the potential for continued mining activity, possibly in a spatially limited area, should be investigated.

Finally, the fact that a mining area has been considered environmentally degraded by local communities for decades provides the opportunity to locate waste management activities there, circumventing the NIMBY (Not In My Back Yard) syndrome.

5. Criteria for the Selection of Post-Mining Land Uses

Focusing on the literature regarding the selection and spatial distribution of land uses after the closure of a mine or quarry, the basic criteria considered are strongly related to the three main components of sustainable development: the economy, society, and the environment. Moreover, six other elements are considered: the site-specific characteristics of the mine, culture, technical issues, governance, regional development, and geoethics [8].

Table 5 presents a list of 112 attributes that have been used so far for post-mining land-use selection in several cases. They cover the whole range of extractive activities in terms of size, type of mineral resource under exploitation, and applied mining method. Moreover, these attributes have been distributed to the following nine criteria: environment, society, economy, technical aspects, mine site characteristics, governance, regional development, and geoethics.

The selection of criteria for land-use designation, along with the subsequent determination of weights among these criteria, can significantly influence the outcome of the decision-making process. This aspect often becomes a focal point of contention among the stakeholders involved. Within the context of land use, suitability refers to the inherent physical capacity of land to support specific uses efficiently and sustainably. Various organizations have published guidelines for land-use planning that outline favorable conditions and limitations for specific land developments [76]. Nevertheless, community pressure remains the predominant factor influencing land-use decisions. With development objectives in mind, the rising demand for specific land uses complicates decision-making. Therefore, decision-making processes should incorporate additional criteria that assess capacities related to social well-being and economic development [77].

Attempting a further analysis of the number of attributes per criterion, it was found that in the various post-mining land-use selection studies conducted to date, for the evaluation of technical aspects, society, and site-specific characteristics criteria 18, 15, and 14 attributes have been used, respectively. The high number of attributes highlights the multi-parametric nature of an environmental restoration project, its critical importance for maintaining social well-being, and the necessity to consider all the unique characteristics of the area that hosted the mining activity. For the remaining criteria, the number of features are as follows: economy with seven (7), culture with six (6), geoethics with four (4), governance with three (3), and environment with three (3), as shown in Figure 2.

Specifically, the attributes listed under the criterion of the environment consider a series of measurable parameters to be taken into account when analyzing the suitability of soil, water, and air for specific land uses. Apart from climate, all the other attributes can be evaluated based on objective measurements collected in the framework of a long-lasting monitoring program that requires special equipment and multi-disciplinary scientific and technical personnel.

The society criterion covers 34 attributes that are usually quantified based on statistics (such as employment and migration) or surveys carried out with the participation of all stakeholders (such as land planning and future employment situation).

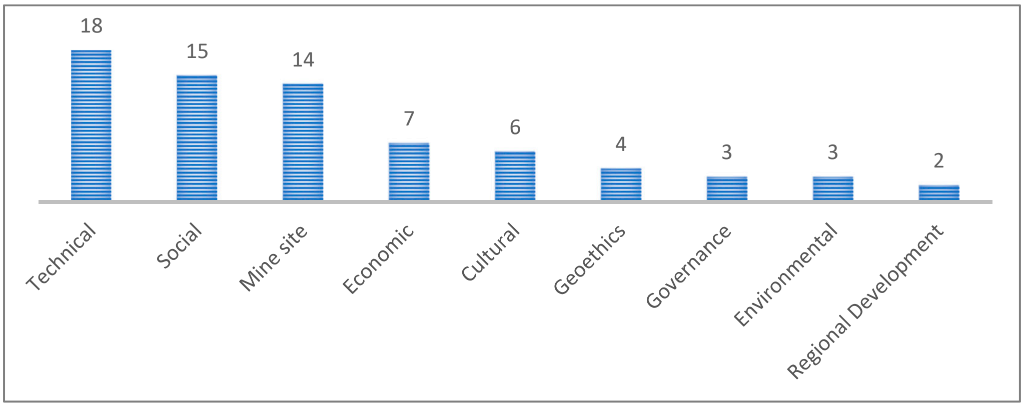

Figure 2. Number of attributes per land use selection criterion.

Table 5. Classification of criteria and attributes for post-mining land-use selection.

Criteria	Attributes		References
Environment	- Soil properties - Climate - Topography - Pit geometry - Geological formations	- Atmosphere - Water - Terrestrial and biological domains - Biodiversity	[8,49,78]
Society	- In- and outmigration to the region - Consistency with local needs - Region demographic characteristics - Social and cultural identification (backgrounds, profile) - Positive changes in welfare - Diversification of skills and technical knowledge - Development of local communities - Future employment situation - Community cohesion - Social structure impact - Regional culture and collective identity - Fears and aspirations of the local community - Safety - Health - Well-being - Land planning - Infrastructures	- Environment - Personal and property rights - Political and institutional stresses - Need to specialist workforce - Changes in livelihood quality - Employment opportunities - Serving the public education - Frequency of passing through the mine site - Ecological acceptability - Tourism attraction (eco-tourism) - Land ownership - Proximity of mine site to population centers - Consistency with local requirements - Social and cultural identity - Skills, abilities, and know-how of human resources - Education level - Impact on existing supply facilities, including operating costs stakeholders	[8,49,79–81]

Table 5. *Cont.*

Criteria	Attributes		References
Economy	- Cost: - Maintenance and monitoring costs - Capital costs - Operational costs - Employment opportunities - Economic development - Costs related to the implementation of the alternative - Cost of monitoring environmental and safety issues	- Time needed to develop the plans - Post-mining land-use economic balance - Funding opportunities or possibilities - Potential of investment attraction - Increase in governmental income - Increase in local community income - Post-mining land ownership - Potential changes in real estate values	[8,49,78,80,81]
Mine site characteristics	Soil: - Physical properties of the soil - Chemical properties of the soil		[80–82]
	Climate: - Evaporation - Frost-free days - Precipitation - Wind speed	- Air moisture - Temperature - Surface water and groundwater - Hydrology	
	Topography: - Surface relief - Slopes - Elevation	- Exposure to sunshine - Physical properties of mine components	
Culture	- Values - Traditions - Education	- Aesthetics - Refinement of behavior	[49]
Technical aspects	- Surface mining method - Shape and size of mined land - Environmental contaminations - Physical characteristics of the mining area - Measures that need to be taken to cope with the type and method of contamination - Characteristics of structures and facilities - Potential for circular economy - Terrain characteristics - Slope stability and other risk factors - Access to reclamation techniques - Accessibility - Traffic frequency of mined land	- Distance to local communities - Availability of reclamation techniques - Closeness to the nearest water supply - Market availability - Current land uses in surrounding areas - Prosperity in the mine area - Structural geology - Distance from special services - Outlook of future businesses - Extreme events potential - Reusing potential of mine facilities - Landscape quality	[8,78,80,81]
Governance	- Governmental policy - National strategy	- Legal and regulatory framework	[8,12]
Regional Development	- Legal framework regarding land management - Regional development strategy	- Regional strategy for climate change	[78,79]
Geoethics	- Local population needs - Natural potential	- Knowledge of mining - Safety and health of the ecosystem	[78,79]

The economy criterion evaluates alternative land uses by considering the relevant costs or carrying out a cost–benefit analysis. Additionally, many other attributes can be incorporated, which analyze the perspectives of economic development, employment opportunities, sources of funding, as well as the potential of boosting the development of specific businesses, such as real estate or tourism.

The mine site characteristics are further divided into three groups of attributes that are related to the soil's physical and chemical properties, climate, and topography. While climate, which is also classified by other scholars to the criterion of environment, is not affected by local mining activities, the soil properties and topography change dramatically due to mining and mineral processing. Thus, the values of the relevant attributes can be crucial for selecting sustainable land uses.

The culture criterion examines the extent to which the land uses produce positive results regarding the cultural characteristics of the area, values, traditions, education, upbringing, aesthetics, and sophistication of behavior [49]. Although closely connected to social issues, culture is often examined separately to emphasize its key role in maintaining relationships of mutual understanding and cooperation between mining enterprises and local communities.

The technical aspects criterion concerns the constraints on the choice of alternative land uses due to technical difficulties, such as the size and morphology of the mining site, the type of pollution and the size of the polluted areas that must be remediated, the reclamation techniques that can be applied considering limitations such as the access to roads and irrigation water, and the possibility to apply circular economy principles to extend the life cycle of existing infrastructures and equipment.

The governance criterion concerns government policies that influence or facilitate the choice of exploitation options in transitional areas based on national, regional, and local development policies and legal frameworks [8]. Paying attention to the details of managing a mine and its end-of-life impacts can significantly improve the impact and attract further funding or other contributions, leading to more development in the area you are restoring [12].

The regional development criterion has been recently added to the land-use selection criteria in order to consider regional targets and strategies but also regulatory restrictions and spatial plans in the decision-making processes. Elements that are usually accounted for include the potential for agricultural, commercial, touristic, real-state, or other economic activities [78,79].

Finally, the geoethics criterion intends to enable decision-makers to develop a set of attributes that consider how the economic activities introduced with the new land uses interact with the local population's needs, personnel skills and expertise, natural and aesthetic values, and ecosystem health (including human), for instance, through the promotion of culture and tourism or by the preservation of geological and mining heritage [78,79].

6. Multi-Criteria Analysis Methods Applicable in Post-Mining Land-Use Selection

The selection of land uses after mine closure presupposes determining suitable and effective criteria. The previous section mentioned the criteria used in the international literature for evaluating optimal land-use options. It was noted that regardless of the site-specific characteristics of the case under investigation, the evaluation of alternative land uses cannot be based on a single criterion. Therefore, the implementation of multi-criteria decision methods, either separately or combined, is required to quantify and assess the examined land uses. Several methods are available, which differ in the way the features are ranked, the logical order of steps, and the background framework. These multi-criteria methods are listed in Table 6.

Table 6. Multiple-criteria decision-making (MCDM) methods.

Methods		References
Cost—Benefit Analysis		[80]
S.W.O.T.		[81–83]
IE (Internal–External) Matrix		[81,84]
Boolean Logic and Fuzzy Sets		[85,86]
AHP—Analytic Hierarchy Process		[77,83,85–88]
IAHP—Improved Analytic Hierarchy Process		[89]
ANP—Analytic Network Process		[90]
ELECTRE—ELimination Et Choix Traduisant la REalit'e		[91]
Fuzzy Logic		[90,92]
FCM—Fuzzy Cognitive Map		[93]
FIS—Fuzzy Inference System		[93]
FANP Fuzzy Analytical Network Process		[93]
GIS—Geographic Information System		[85,88,90,94–96]
SMART—Simple Multi-Attribute Ranking Technique		[85]
LP—Linear Programming		[85]
PROMETHEE—Preference Ranking Organization METHod for Enrichment of Evaluations		[88]
TOPSIS—Technique for Order of Preference by Similarity to Ideal Solution		[79,86,89,97,98]
SAW—Simple Additive Weighting		[99]
Likert Scale		[81,98–101]
IDEF0		[102]
SIMUS		[79]
SMARTER		[79]
Hybrid	SIMUS, TOPSIS, SMARTER.	[79]
	SWOT, IE matrix	[81]
	AHP, SWOT	[83]
	MSLA, GIS, Fuzzy, Boolean Logic, AHP, SMART, Linear, Integer Programming	[85]
	Boolean Logic and Fuzzy Sets	[85,86]
	Fuzzy, AHP, TOPSIS	[86]
	PROMETHEE, AHP	[88]
	IAHP, TOPSIS	[89]
	GIS, ANP, MCDM, Fuzzy Logic	[90]
	AHP, ELECTRE	[91]
	GIS, Fuzzy	[92]
	FIS, FANP	[93]
	AHP, SAW, TOPSIS, Compromise Programming	[99]
	AHP, TOPSIS	[96]

Based on the literature review, this study recorded 22 multi-criteria methods that have been used for assessing alternative land uses. The AHP method was the most commonly used, followed by TOPSIS, GIS, and SWOT analysis, while for recording the views of stakeholders, the Likert scale method prevailed. Moreover, it has been found that a single method is rarely used for determining the optimum land use. In most cases, two or even more methods are incorporated in a hybrid approach to enhance the effectiveness of land-use selection. In Table 6, fifteen (15) hybrid methods are listed.

More specifically, cost–benefit analysis has been used in the past to determine if the US SMCRA was going to impact the coal mining industry [84]. It is a key component of many current land reclamation decision support systems. The basis of making decisions using cost–benefit analysis is that if the benefits are greater than the costs, that project should be chosen. Another way to determine which solution, and to what extent it is to be used, by cost–benefit analysis is when the marginal net benefit equals zero, or the closest to zero.

SWOT analysis matrices are used to identify all possible general PMLU options based on mine reclamation objectives, with the purpose of revealing positive forces that work synergistically and potential problems that need to be recognized and addressed.

The IE (Internal–External) matrix method is used to determine the strategic position of each PMLU option. The IE matrix examines both internal and external factors at the same time.

The AHP has been used extensively for decision-making, including the determination of PMLU. An AHP hierarchy is a structured means of modeling the decision at hand. It consists of an overall goal, a group of options or alternatives for reaching the goal, and a group of factors or criteria that relate the alternatives to the goal [85]. The AHP is useful when the decision-maker has a problem characterized by multiple decision criteria and multiple choices, sometimes noted as a multi-objective decision problem [81]. The basis of AHP is to break the overall decision problem down into simple sections: objective, criteria, and alternatives. Similarly, an Improved AHP is a comprehensive method for determining weights of the assessment indices, which combines the AHP weight method and the entropy method to reflect the empirical judgments of experts and objective variability of assessment data. The analytic network process (ANP) is a more general form of AHP used in multi-criteria decision analysis. AHP structures a decision problem into a hierarchy with a goal, decision criteria, and alternatives, while the ANP structures it as a network.

In mining engineering, ELECTRE model could be applied to achieve some outranking relationships between post-mining land uses through mined land suitability analysis [90].

Fuzzy sets allow for any real value from zero to one, in the case of truth values based on a condition. This contrasts with Boolean, which gives a value of zero or one based on a logical true or false condition. Growth curves or functions allow for a transition from value zero to one or vice versa. Fuzzy sets are excellent for mathematical modeling because they allow for uncertainty. This logic is useful when determining land suitability scores.

Continuing with fuzzy logic methods, a Fuzzy Cognitive Map (FCM) is a cognitive map, within which the relations between the elements (e.g., concepts, events, project resources) of a "mental landscape" can be used to compute the "strength of impact" of these elements. Additionally, the Fuzzy Analytic Network Process (FANP) is a widely used multi-criteria method capable of handling interaction among the criteria and linguistic variables. Finally, the Fuzzy Inference System (FIS) is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned.

GIS is used to prioritize land-use zoning in the context of mine reclamation planning through spatial information. Using spatial information, such as distances, elevations, and slope angles, a list of sites by priority level can be created.

Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) is a top-ranking method that is quite simple to conceptualize and implement compared to other multi-attribute analysis methods. It is well suited to problems such as MLSA, where a finite number of alternatives need to be ranked, taking into account multiple, sometimes conflicting, attributes.

Simple Multi-Attribute Ranking Technique (SMART) uses a ranking system rather than pairwise comparisons to create weights that are transitive; that is, uses a direct ranking of criteria based on importance to help select the best option. The criteria scores are always transitively consistent. The advantage of this is the decision-maker is able to identify how much more an attribute is valued over another much easier than with AHP since the rankings are direct and will result in transitive values.

TOPSIS is based on the fundamental premise that the best solution has the shortest distance from the positive-ideal solution and the longest distance from the negative-ideal one. Alternatives are ranked using an overall index calculated based on the distances from the ideal solutions.

Linear programing is a technique used for optimizing an objective function based on constraints. Linear and integer programing have five components to any problem: (1) the available choices, (2) criteria of alternatives, (3) weights on the criteria, (4) scores of alternatives by criteria, and (5) constraints.

The Simple Additive Weighting (SAW) method can be regarded as the most intuitive and simplest method for dealing with multi-criteria decision-making (MCDM) problems since the linear additive function can represent the preferences of the decision-makers (DM). The SAW method is the simplest MADM method for master data management. The method is widely used in many areas because it is easy to use and understandable for the decision-maker.

A Likert scale is the most widely used approach to scaling responses in survey research, such that the term (or more fully the Likert-type scale) is often used interchangeably with rating scale, although there are other types of rating scales.

IDEF0 stands for Integration Definition for Process Modelling, a public-domain methodology used to model businesses and their processes so they can be understood and improved. It is a type of flowchart diagram.

The SIMUS method allows decision-making to assess different alternatives in the case of certainty. SIMUS is a hybrid method based on linear programing, weighted sum, and outranking methods. This method models MCDA problems where multiple objectives need to be met, dependent criteria are in place, alternatives, or projects require precedence by other alternatives, and it does not impose limits to the number of criteria or alternatives used.

The Simple Multi-Attribute Rating Technique Extended to Ranking (SMARTER) is a method that can be applied through a questionnaire, designed specifically for the site and problem under appraisal. The aggregated answers give weights to criteria that are then used in TOPSIS or SIMUS methods.

The question at hand is which method or combination of methods is optimal for selecting post-mining land uses. There is no doubt that techniques such as cost–benefit analysis and SWOT analysis can be employed in decision-making processes within a mining enterprise, involving managers and executives who approach the problem from a similar perspective. Furthermore, it is also clear that whether selection criteria and planned land uses exhibit spatial variability within the study area, GIS emerges as the most dependable tool for integrating alphanumeric data with map layers, and for spatially analyzing and visualizing data. Regarding the choice between MCDA methods, there is a rich literature on this subject [103–105]. Several factors influence this choice, such as the following:

- The nature of results the method is expected to bring, e.g., aiming at grading or ranking alternative solutions;
- The scale of analysis, e.g., intra-enterprise or at a regional or national level;
- The requirements and preferences, e.g., the number of alternatives to compare or judge, scales, acceptance of compensation among criteria, handling of imperfect knowledge, etc.;
- The criteria type (e.g., in terms of data format and weights);
- The practical considerations (e.g., software requirements and associated costs).

Nevertheless, instances exist where decision-making methods were selected randomly, or based on the decision-maker's knowledge and experience, or due to the availability of required software within the organization.

7. Synopsis and Discussion

In the following paragraphs, the main issues raised by the preceding global review are summarized, briefly pointing out certain critical implications as well as the main limitations of this study.

The literature review conducted in this study highlighted that the rehabilitation of surface mines that close due to resource depletion, changes in economic conditions, or within the framework of the energy transition policy, is a practice applied in all countries. In most countries, national legislation requires mining companies to undertake a series of interventions aimed at restoring the land to its pre-mining state. Additionally, in countries with strong supervisory mechanisms, the cases of insufficient mine land remediation or abounded mines have been eliminated. Nevertheless, few countries provide the legal framework for alternative interventions in post-mining areas, which are based on circular economy and sustainable development principles and can mitigate the economic and social impacts of large-scale mining activity closures. The examples of innovative land uses mentioned earlier are good practices implemented either through the mining companies' ESG strategies or by central or regional governments that gained jurisdiction over a mining area after its abandonment by the previous owner.

Regarding land uses developed after the closure of a surface mine or quarry, forests, agricultural lands, and livestock farming cover most acreage of the restored mines globally. However, this study found that there are also many alternative land uses related to residential/urban development, recreation activities, and industrial facilities. In addition, recently published articles indicate an increasing trend in the installation of Renewable Energy Sources (RES), particularly photovoltaic parks. This is also the case for remining rock dumps and dried tailings, due to the growing demand for minerals required for digital and energy transitions and the difficulty many companies face in acquiring new mineral deposits. Another significant factor in planning new land uses is the accumulation of water in the final pits of surface mines. This water can be utilized for recreation and sports, energy storage in pumped water storage facilities, irrigation of agricultural lands, aquaculture, fire suppression, and wetland creation. To illustrate the many post-mining land-use options available, it is worth mentioning that, on the occasion of the Eden project to rehabilitate mines in Cornwall, England, two papers have been written on 101 things that can be done with a hole in the ground (i.e., a surface mine) and 101 more things that can be done with the "stuff" next to this hole [6].

Although land-use selection is guided by legal and regulatory requirements related to land reclamation, multiple criteria methodologies are also used, based on various attributes classified in the nine groups of criteria identified in the literature. The large number of attributes used to evaluate, quantitatively or qualitatively, these criteria is noteworthy. It indicates the need to adapt each decision-making process to the specific characteristics of the area that hosted the mining activity. While this adaptation is necessary to utilize all available information in the area under investigation, it also facilitates predetermined decisions by the entity conducting the land-use selection process. Such practices are, of course, ethically unacceptable.

Finally, it was found that twenty-two different multi-criteria evaluation methods and fifteen hybrid methods were used to evaluate the proposed alternative land uses. These methods, either individually or in combination, provided a quantitative assessment and contributed to selecting the optimal land use. Among these, the use of GIS is the most widely applied method in choosing land uses in large-scale surface mines. The use of GIS facilitates monitoring the spatial variations of the values of the various attributes examined and supports decision-making for the spatial distribution of different land uses within the reclaimed mine.

The question that arises, based on all the above, is to what extent the land-use selection methods and criteria presented in the rich literature have transcended the boundaries of academia and been utilized by mining companies, regional authorities, and the central governments for decision-making purposes? A second question, directly related to the first, is whether the time is ripe for spatial planning to be based on the use of MCDA methods to regulate post-mining land uses?

Regardless of how open and receptive to new ideas the industry and authorities may be, various issues require careful decisions. Some fundamental cases that can be distinguished in the relevant practice include:

Cases requiring measures to protect the environment and public health. These are mining areas where the geochemical characteristics of the extracted rocks and/or the use of hazardous substances during extraction and, primarily, during ore processing have caused the release of pollutants into the environment, in concentrations that possibly exceed the specified limits. In such cases, alternative land uses are restricted to those capable of limiting pollution dispersion in the broader area and gradually reducing pollutants' concentrations within the former mining area. A characteristic example is the asbestos quarry located at

Zidani, in the region of Western Macedonia, Greece, where eight years after the completion of restoration works, a program is still in place to monitor asbestos fiber concentrations in the quarry's surrounding water bodies [106]. Numerous similar cases are cited in the literature regarding monitoring and control of acid mine drainage [107,108].

Cases of many small-scale, abandoned mining sites located in a region. Most abandoned mines and quarries hosted small-scale extractive activities that suddenly stopped after the bankruptcy of their operator. Typical examples include quarries for aggregates and building materials production, which are found in all regions and countries supplying the local construction sector, as well as small and temporary quarries developed to produce materials for large-scale public projects, primarily road construction. The authors of this study are currently conducting research aiming at proposing a method for selecting optimal land uses simultaneously for a set of seventeen quarries located within the same geographical unit (municipal boundaries). In this direction, some jurisdictions, such as in Queensland, Australia, have already started to acknowledge the need for wider regional planning approaches in which post-mining land-use selection considers regional and local planning strategies, the surrounding landscape, and community views. Shifting thinking from site-specific planning to regional scale has offered strategic advantages, including the ability to consider options that are only viable at scale and to reinstate larger expanses of native bushland or functional agricultural land [102].

Cases of large open-pit mines. These are the most complex cases, offering significant advantages over all others but also posing much greater challenges. Focusing, for instance, on open-pit coal and lignite mines that plan to cease operations in the near future due to energy transition policies, the following peculiarities regarding land-use selection can be highlighted:

- The regulatory framework is based on environmental impact assessment studies and environmental permits that describe the land rehabilitation works planned to be carried out after mine closure before the beginning of the mine operation. Supervisory authorities are usually stricter with large mining companies. At the same time, large companies have the means to influence developments.
- Mine operations decisively influence land restoration and land-use alternatives. For instance, whether there has been provision for separate excavation and storage of topsoil or whether overburden materials are deposited within the pit or in external dumps are choices that dictate post-mining developments.
- Land restoration projects have commenced long before, and rightly so, decisions to cease operations, and, to some extent, have shaped land use for specific areas.
- The mine land, due to its extensive acreage, represents one of the main assets of the mining enterprise and can be utilized for new business activities. A characteristic example is the installation of photovoltaic parks and energy storage systems in the lignite mines of RWE in Germany [109].

Considering the above, large-scale surface mines provide an excellent field for the implementation of multi-criteria methods, in combination with GIS that will analyze the spatial changes of criteria and visualize the result, which will be the allocation of various land uses within the area under examination [93].

The main limitation of the present global review is that to understand more thoroughly the connection between policy theory and practice, it is important to proceed to a more in-depth and comparative analysis of specific cases. This task is planned as a second stage of the present research. In addition, this literature review could be extended in the future to include cases of land rehabilitation and land-use selection that did not yield the expected results, contributing in this way to avoid failed interventions in the future.

8. Conclusions

The exploitation of mineral resources constitutes a fundamental component of national and regional economies and is strongly interwoven with the prosperity of local communities. The extraction of raw minerals in open-pit mines poses threats to the environment unless specific mitigation measures are implemented. Open-pit mining typically lasts several decades and becomes an integral part of the regional economy. Therefore, its closure results in significant social disruptions. At the same time, large areas with extensively transformed landscapes are often permanently excluded from further use. The revitalization of these landscapes and the boosting of the regional economy is a long-lasting and complicated process that requires appropriate planning and design based on an interdisciplinary approach, as well as close collaboration between different stakeholders and the local communities.

From the literature reviewed in this paper it becomes evident that today, in most countries, the appropriate conditions have been created to avoid past mistakes and eliminate instances of mines being abandoned without any intervention. Particularly in cases where mines are hastily closed due to the energy transition, local communities, supervisory services, and most stakeholders seem to be changing their priorities. While the traditional goal was the restoration of the ecosystem and the return of its functions to the pre-mining state, the current need for mitigating economic and social impacts prioritizes the rehabilitation and repurposing of mining land with a focus on the development of the local communities. While the old goal presented technical difficulties in achieving, the new goal requires substantial financial support and will be judged in the long-term in terms of accomplishing sustainable development goals.

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