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Abstract: Mining activities often generate important amounts of extractive waste, and as a consequence, environmental impacts that affects all factors to a greater or lesser extent. Depending on a variety of variables, the impact can be permanent or temporary, reversible or irreversible, negative or positive. This study conducted research on the status of closure and remediation processes of mining areas in Romania, specifically in the counties of Maramureș, Suceava, Harghita, Alba, Hunedoara, and Caraș-Severin. Furthermore, based on the type and level of pollution, the degree of application of remediation techniques for water and soil pollution in the investigated mining areas was studied. From the analysed information, it is evident that although the closure and remediation process started in Romania over 20 years ago, unfortunately, to this day, the technical projects, technical assistance, and execution of closure and remediation works have not yet completely solved the complex environmental issues in the mining sector. Most of the tailing ponds and waste piles of former mines continue to pose permanent specific risk to the environment and the population. This study concludes that the mining sector in Romania, although it has the necessary techniques and technologies for the ecological rehabilitation of degraded lands related to the Extractive Waste Facilities and the elimination of negative impacts on the environment and public health, has not yet been able to fully concretize its remediation efforts.

Keywords: heavy metals; mining activities; pollution; remediation

1. Introduction

Valuable mineral substances represent the essential foundation for any industrial activity, and therefore, the premise for the economic growth of any nation [1,2]. One of the main goals of the mining industry is to satisfy society's demand for resources for infrastructure development or the production of used goods, in order to increase the quality of life of the population [3–5].

The extraction of valuable mineral substances creates an imbalance in the natural environment, both in the extraction sites themselves and in the areas where the wastes resulting from the stages of exploitation and processing have been deposited [6–9].

Moreover, it is recognized that the mining industry is, worldwide, one of the main sources of waste production, the areas occupied by dams and tailings deposits, being more and more significant. In the last decades, the extraction of mineral raw materials has reached impressive quantities [10,11], e.g., about 550–750 Mt of extractive waste being generated in the EU every year [12]. As a consequence of the planet's population growth and the pace of economic expansion in developing countries, the demand for raw materials is set to increase further, thereby resulting in a significant environmental pollution as an outcome of mining activities, consequently impacting both the surrounding environment and public health [13,14].

On the EU 27 level, the mining and quarrying sector is the second main source of waste, accounting for 26.3% of the total waste generated, and at the Romania level for 24.3% [15,16]. In any case, this huge volume of material will require proper management and even more, the integration of the extractive waste management into the mine planning for every mineral resource.

Mining is considered one of the primary sources of heavy metal contamination in the environment. The extraction of precious metals and minerals releases hazardous metallic substances into the soil, water, and atmospheric air, thereby augmenting their existing quantities [17–19].

Some heavy metals are persistent and irreversible, degrading the quality of water, atmosphere, and agriculture [20–22]. They also raise significant concerns regarding the health of humans, plants, animals, and microorganisms due to contamination and accumulation in their respective food chains [23–25]. Owing to these characteristics, heavy metals are non-biodegradable and persist in the environment for extended periods [26,27]. The primary heavy metals causing substantial concern in this category include nickel (Ni), zinc (Zn), copper (Cu), lead (Pb), arsenic (As), selenium (Se), cadmium (Cd), chromium (Cr), manganese (Mn), cobalt (Co), and mercury (Hg) [28–30].

According to reports from 2017, Romania holds the record for the highest percentage of mining waste accumulates from the extractive industry, accounting for over 85% of the total in Romania (the European average is slightly above 25%), much of which originates from historical mining activities [31]. Prior to 1989, the mining industry in Romania pursued a development strategy rooted in the concept of self-sufficiency [32]. The process of closure and ecological restoration of certain mining sites commenced in Romania in 1998, in accordance with the prevailing specialized legislation. The closure and ecological restoration of waste rock piles and tailings ponds are undertaken with consideration for the overall stability of these structures, as well as their integration into the surrounding environment [33,34]. This includes the reclamation of land areas occupied by mining waste deposits.

Unfortunately, up to the present moment, the technical projects, technical assistance, and execution of closure and ecological restoration works have only addressed the complex environmental issues in the mining domain in a limited number of sites. Regarding waste rock piles, ecological restoration methods have been applied to only 65 out of a total of over 500 piles [35–37].

One of the priority tasks assumed by the Romanian Government through the Treaty of Accession to the European Union is taking responsibility for the restoration of the environment affected or altered over time by the impact of extractive activities. This is done through the development and funding of well-founded annual programs aimed at the effective implementation of the Ecological Reconstruction Process for sites impacted by mining activities.

Based on the provisions of Emergency Ordinance no. 51/1997 regarding certain measures for the conservation and closure of mines, the conservation and closure of non-profitable mines and quarries started in 1998 [38]. This activity was initially regulated by Mining Law no. 61/1998, which was subsequently amended by Law no. 85/2003 and Government Decision no. 1208/2003 for the approval of implementing norms [39–41].

Starting from 1998, through 11 Government resolutions, the permanent closure, conservation, and post-closure environmental monitoring of 556 mines were approved, located within the administrative territory of 227 local communities in 28 counties (from a total of 41). Within these mining sites, a significant number of industrial waste deposits fall under the scope of prevailing legislation concerning the storage and secure containment of hazardous waste. This includes 78 tailings ponds with a total stored volume of 341.31 million cubic meters and an area covering approximately 1,770 hectares, as well as 675 mining waste heaps with a volume of 3,101.92 million cubic meters and an area of approximately 9,260 hectares [37].

For these sites, it is imperative to ensure the ongoing stability of the mining deposits over time and to conduct essential activities and measures for securing them. This involves addressing 2,504 surface-related mining structures (such as galleries, shafts, and adits) that allow access to the underground atmosphere, which is artificially maintained.

Mining sites where the extraction of valuable mineral substances has been ceased exhibit a high degree of associated risk due to subterranean voids that can result in the accumulation of toxic and

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potentially explosive gases, subsidence phenomena, uncontrolled surface collapses, and significant landslides. The stability of hazardous waste deposits is also compromised, posing catastrophic consequences for adjacent communities and the surrounding environment, with potential transboundary effects.

Delays regarding the execution of greening works on sites affected by the mining industry occurred both as a consequence of the under-funding of the closure and greening projects and because of the major risks inherent at the mining sites where non-hazardous mining wastes are stored [35–37]. Another difficult issue is represented by the uncertain legal situation of the lands on which closure and greening works are being carried out. The execution of the modernization works of the mine water treatment stations located in the patrimony of the Ministry of Economy is conditioned by the clarification of the legal regime of the lands on which they are located. The delays in this approach are compromising the greening works already carried out [35–37].

The recovery of the residual valuable minerals from extractive waste is not a widely applied practice in the EU, but could represent the key contribution to a more circular economy. Without the appropriate management of the extractive waste, this activity may be neither economic nor sustainable. Aligned with the European Union's Circular Economy Package, the intention is to harmonize Directive 2006/21/EC with the Circular Economy Package's provisions [42]. This alignment involves incorporating an annual target for the management of mining waste.

Mining waste holds a distinct status based on the category it falls into (hazardous or non-hazardous). The potential treatment methods vary depending on this categorization, encompassing mechanical, physical, biological, thermal, or chemical processes, or a combination thereof, applied to these mineral resources.

Contaminated sites often experience physical disruptions such as geotechnical in-stability and erosion due to climatic factors, alongside biological alterations and chemical contamination. Cleaning and remediating locations tainted by mining waste represent significant environmental challenges in this century. Minimizing the environmental impacts of mining activity (including processing stage) contributes to improving the social perception and acceptance of mineral resource extraction in any region. One of the primary steps toward achieving this goal involves evaluating ecological resources (including receptors, like humans), ecosystem structure and function, as well as the levels and consequences of contamination.

This study undertook research into the closure and ecological restoration processes in selected mining areas of Romania, specifically in the counties of Maramureș, Suceava, Harghita, Alba, Hunedoara and Caraș-Severin. Additionally, based on the type and extent of pollution, the degree of implementing remediation techniques for the polluted water and contaminated soil in the investigated mining zones was examined.

2. Study Area

Romania is mentioned in various specialized documents as having made a special contribution to the world mining production, with various useful mineral substances and especially with noble metals [43,44].

Romania has a rich history of mining activities, even spanning millennia, with notable mining districts that have contributed significantly to the nation's economic development. Among these districts, the Apuseni Mountains, Baia Mare, Banat and East Carpathians regions stand out as historically significant centers of mining and mineral extraction.

The *Apuseni Mountains*, situated in the western part of Romania (Hunedoara and Alba counties), have been a region of mining activity for centuries, renowned for its diverse mineral resources, including gold, silver, lead, zinc, and other precious and base metals. The mining heritage of the Apuseni Mountains dates back to the Roman period, and over the centuries, the area has seen a complex interplay of mining techniques, from traditional practices to more modern methods [45,46]. The landscape of the Apuseni Mountains is dotted with mine shafts, galleries, and remnants of past mining endeavours, showcasing the historical importance of this district to Romania's mining legacy.

The Apuseni Mountains are geologically divided into two significant structural units: the South Apuseni Mountains, also known as the Metaliferi Mountains, and the North Apuseni Mountains. Mining activity, particularly in the Metaliferi Mountains, has a rich history dating back to the first centuries AD [45,47]. The presence of well-preserved mining works and numerous archaeological discoveries provide evidence of early gold extraction in this region. It's interesting to observe that the Metaliferi Mountains are characterized by a dominance of gold compared to the northern Baia Mare mining district, where lead and zinc are the predominant metals. Mining activities have persisted continuously, with a growing interest in various other metals as time has passed.

The South Apuseni Mountains are renowned for their abundance of non-ferrous and precious minerals, hosting some of Europe's world-class ore deposits. These notable deposits include already famous Roșia Montană, Roșia Poieni, Barza-Brad, Stănija, Baia de Arieș, and Săcărâmb mining sites [46,47].

The *Baia Mare region*, located in the northern part of the country (Maramureș county), has also played a pivotal role in Romania's mining history. Baia Mare has a rich history of extracting precious metals, including gold and silver. The city itself has been associated with mining since medieval times, and its mining heritage is reflected in its architecture and culture. The Baia Mare region was known for its thriving mining industry during various historical periods, contributing to both local prosperity and the broader economic growth of Romania. The northern portion of Romania, mostly occupied by the Baia Mare mining district, has a very complex geological structure that partly explains the first-class mineralogical richness of this area.

Neogene volcanic formations played a prominent role in the formation of substantial ore deposits, primarily of the vein-type variety. Within this region, there is a notable presence of volcanic structures followed by shallow intrusive bodies in the Oaş and Gutâi Mountains. The vein deposits in the region are predominantly enriched with lead (Pb), zinc (Zn), and copper (Cu). They also contain, to a lesser degree, gold (Au) and silver (Ag). In some cases, these deposits exhibit distinct vertical zoning patterns [47,48].

However, along with the economic benefits, both districts have also faced environmental challenges due to mining activities. The Baia Mare region gained international attention in 2000 due to a significant cyanide spill, which led to widespread pollution of rivers and ecosystems. This incident underscored the importance of responsible mining practices and environmental safeguards in mining districts.

The *Banat region*, situated within the South Carpathians (Caraș-Severin County), holds historical significance as it is home to numerous ore deposits. What sets this region apart and contributes to its distinguished reputation is the presence of skarn deposits, a geological feature not found elsewhere in the entire Carpathian Mountain range. This skarn belt extends for approximately 70 kilometres and encompasses mineral deposits of considerable importance, both in terms of industrial significance and the exceptional richness of minerals. In the northern part of the skarn belt, one primarily encounters pure skarn deposits, characterized by the dominance of iron ores, as exemplified by the Ocna de Fier deposit. Furthermore, in this northern area, there are skarn deposits where lead and zinc ores prevail, as evidenced by Dognecea. In the south area within the skarn belt, the composition of ores becomes more diverse, featuring a variety of metals. At Moldova Nouă, the ores in this region are polymetallic and exhibit a distinct abundance of copper. Remarkably, in this area, the copper-rich skarn ores coexist with porphyry copper ores [47].

The *East Carpathians* (Suceava and Harghita counties) comprise numerous geological units characterized by metamorphic rocks. These metamorphic rocks are partially overlaid by Triassic sedimentary rocks, Cretaceous and Paleogene flysch deposits, as well as Miocene molasse deposits. Additionally, these metamorphic rocks have experienced intrusive events. There's also a volcanic chain that spans from the Miocene to the Quaternary period, covering a substantial area from the Călimani Mountains in the north to the Harghita Mountains in the south. Except for the mineral deposits and occurrences associated with the Ditrău alkaline massif, most other occurrences typically are of disseminated mineralization [47].

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The pyrite and copper-lead-zinc ore belt, situated within the Tulgheş metamorphic rocks, encompasses three significant deposits: (i) Fundul Moldovei, located near Câmpulung Moldovenesc; (ii) Leșu Ursului, situated east of Vatra Dornei, and (iii) Bălan, found in the southeast of Gheorghieni. These ore deposits are typically abundant in pyrite. The minerals within these deposits often exhibit porphyroblasts and, at times, display well-defined banding. In the East Carpathians, uranium ores have been discovered at four distinct locations within the Paleozoic Tulgheș Series. The Tulgheș Series constitutes a basement unit characterized by low-grade metamorphism [44].

Situated near the structural boundary with the underlying flysch to the east, in the eastern Bistrita Mountains, lies the Crucea deposit, formerly known as Crucea-Botusana. This deposit currently holds the status of the largest uranium mine in Romania. Production activities at this site occurred over two distinct periods: from 1964 to 2016 and then recommenced in 2018. In total, the cumulative output from this location has amounted to a staggering 30×10^9 kilograms of Uranium ore [49].

3. Results

In recent years, efforts have been made to balance the preservation of the historical significance of these mining districts with the need for sustainable practices and environmental protection. The Apuseni Mountains and Baia Mare continue to be areas of interest for researchers, historians, and environmentalists, as they represent the complex relationship between mining, heritage, and environmental management in Romania.

In this paper we selected as the study area the zone covered by six counties (Maramureș, Suceava, Harghita, Alba, Hunedoara and Caraș-Severin), where Figure 1 indicates 234 records (63.24% of the total metal deposits in Romania at that time), including the large deposit of Au and Ag at Rosia Montana, 201 small deposits (66.78% of the total number of small deposits) and 32 occurrences (47% of the total number of metallic mineral occurrences in the country **[50–52]**).

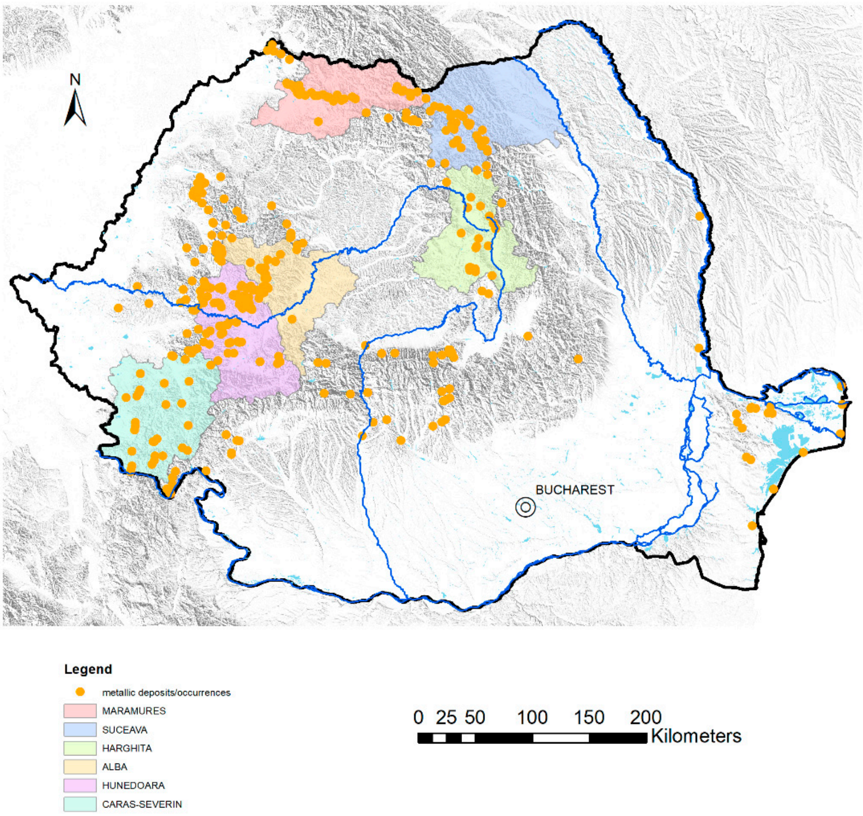

Figure 1. The deposits and occurrences of metallic mineral substances in Romania, at the level of the 1980s.

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According to the data presented by Fodor [48], at the level of the 2000s, 112 operational mining targets were nominated in Romania for the continuation of the production activity, of which 68 with coal, 34 with metallic ores, 3 in the production of uranium and 7 salt mines. Romania has exploitable geological reserves totalling: 40 million tons of gold-Argentine ores, 90 million tonnes of polymetallic ores, 900 million tons of copper ores, 4 billion tons of salt, etc.

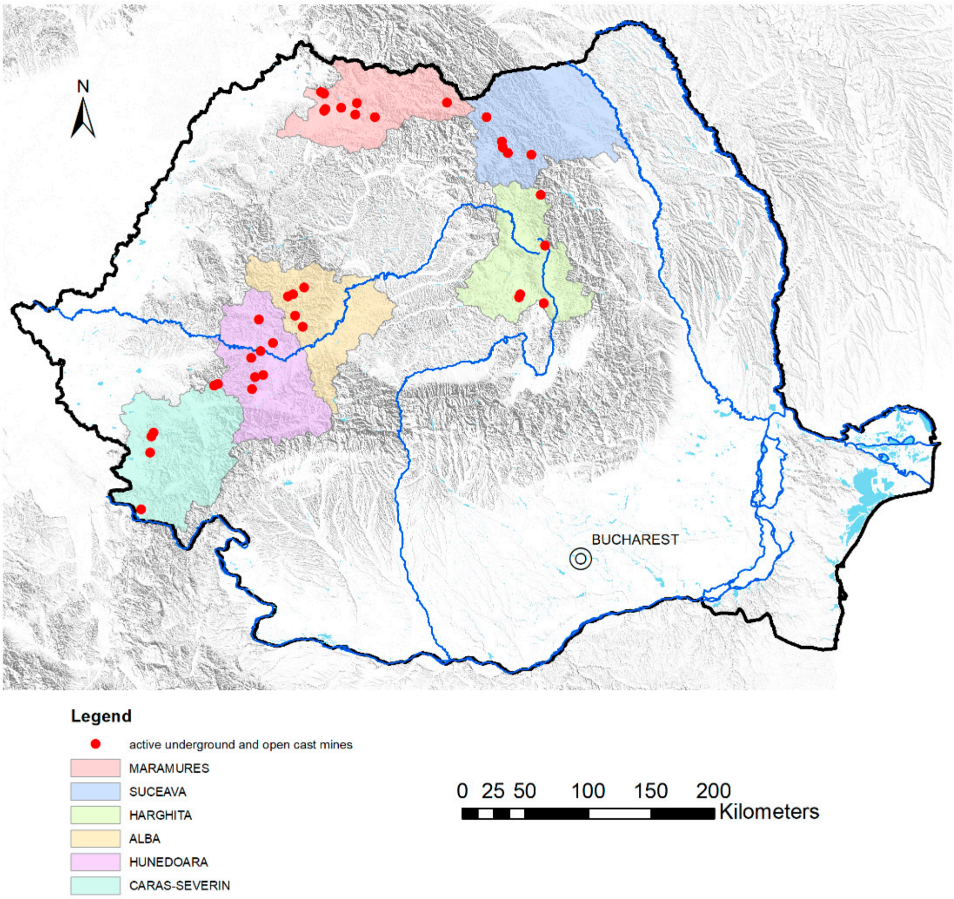

Figure 2. Exploitation sites of metallic mineral substances in Romania for selected counties, at the level of the 2000s.

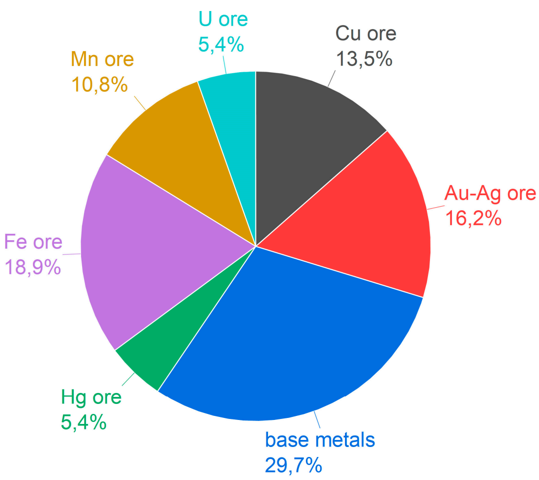

Figure 3. Percentage of types of ore exploited in Romania in the year 2000 for selected counties.

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In Romania, around year 2000, there were 35 mines in operation in the selected counties (Table 1).

Table 1. Substances in exploitation in Romania around year 2000 [44].

County	Location	Substance
Alba	Roșia Poieni	Cu ore
	Roșia Montană	Au, Ag ore
	Baia de Arieș	base metals (Cu, Pb, Zn) and Au
	Zlatna	Au, Ag ore
	Izvorul Ampoiului	Hg ore
Caraș-Severin	Moldova Nouă	Cu ore
	Ocna de Fier	Fe ore
	Rușchița	Fe ore
	Dognecea	Fe ore
	Rușchița	base metals (Cu, Pb, Zn)
	Ciudanovița	U ore
Harghita	Lueta	Fe ore
	Vlăhița	Fe ore
	Bălan	Cu ore
	Sântimbru	Hg ore
	Tulgheă	U ore
Hunedoara	Teliuc	Fe ore
	Ghelar	Fe ore
	Deva	Cu ore
	Barza	Au, Ag ore
	Certej	Au, Ag ore
	Muncelu Mic	base metals (Cu, Pb, Zn)
	Boița Hateg	base metals (Cu, Pb, Zn)
Maramures	Baia Borșa	Cu ore + base metals (Pb, Zn)
	Baia Sprie	base metals (Cu, Pb, Zn)
	Băiuț	base metals (Cu, Pb, Zn)
	Cavnic	base metals (Cu, Pb, Zn)
	Ilba	base metals (Cu, Pb, Zn)
	Nistru	base metals (Cu, Pb, Zn)
	Săsar	Au, Ag ore
	Șuior	Au, Ag ore
Suceava	Vatra Dornei	Mn ore
	Iacobeni	Mn ore
	Argestruțu	Mn ore
	Dadu-Cârlibaba	Mn ore
	Leșu Ursului	Cu ore + base metals (Pb, Zn)

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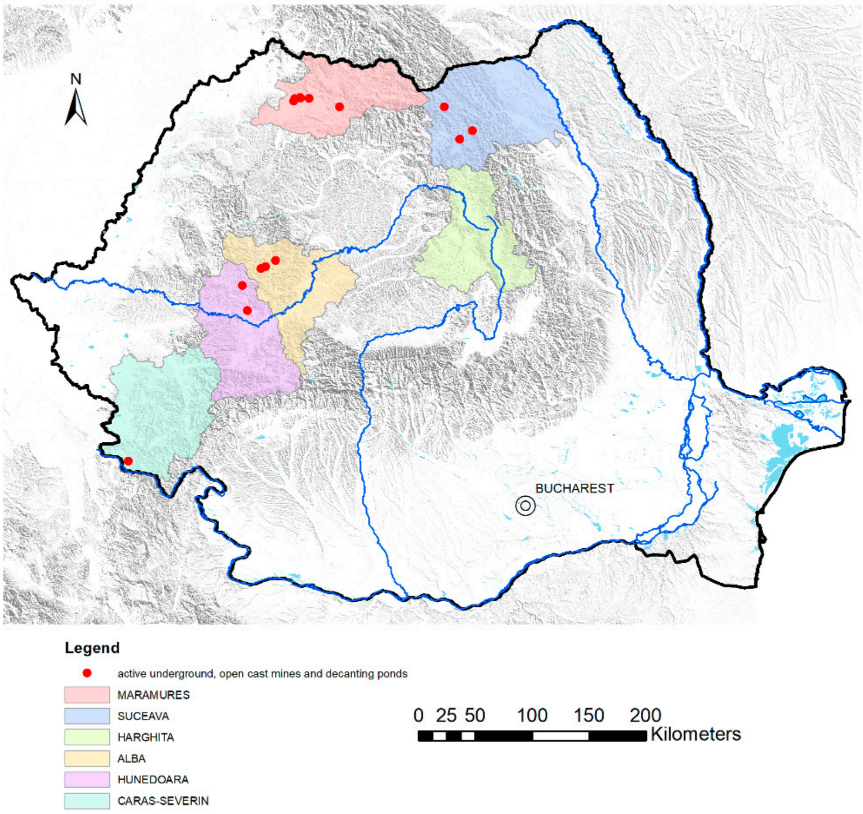

Figure 4. Exploitation sites of metallic mineral substances in Romania for selected counties, at the level of 2021.

From the list of deposits with exploitation licenses in the selected counties (Table 2), in 2023 only the deposits of Roșia Poieni and Roșia Montană were in operation.

Table 2. Exploitation Licenses from National Agency for Mineral Resources ANRM [53] at year 2021 level.

County	Location	Substance
Alba	Roșia Poieni	Cu ore and ore with low Cu content
	Roșia Montană	Au and Ag ore
	Baia de Arieș	Au and Ag ore
Caraș-Severin	Moldova Nouă - banatites quarry	Low content Cu ore
Hunedoara	Rovina	Cu ore with Au
	Certej	Au and Ag ore
Maramureș	Baia Sprie	base metals
	Băiuț	base metals
	Săsar	Au and Ag ore
	Decanting pond Aurul Săsar	mining waste product
	Aurul S.A. processing plant	mining waste product
	Decanting pond - Central Floatation	mining waste product
	Decanting pond Meda	mining waste product
Suceava	Ulm	Mn ore
	Crucea Botușana	U ore
	Mănăila	base metals

The process of mine closure and remediation started in 1998 and it was carried out in eleven phases, until 2010, being regulated by Government Decisions (HGs), listed in Table 3.

Table 3. Government Decisions regarding of the process of mine closure and remediation.

Law	Phase	Official Monitor no./date
HG 816/1998 [54]	I	443/20.11.1998
HG 17/1999 [55]	II	14/20.01.1999
HG 720/1999 [56]	III	443/13.09.1999
HG 493/2000 [57]	IV	284/22.06.2000
HG 602/2001 [58]	V	369/09.07.2001
HG 898/2002 [59]	VI	645/30.08.2002
HG 926/2003 [60]	VII	602/25.08.2003
HG 1846/2004 [61]	VIII	1112/27.11.2004
HG 1008/2006 [62]	IX	692/14.08.2006
HG 644/2007 [63]	X	469/12.07.2007
HG 997/2010 [64]	XI	692/15.10.2010

The Government Decisions (HG) referred to the closing and remediation of the mine areas, listed the mines to be closed and the costs of preparing the documentation, closing and ecologisation actions for each mine, as well as the costs of conservation (where it was the case). There is an obligation of a post-closure monitoring program, mentioned also in the Mining Law [54] in article 53, and the monitoring implementation is paid by the License Holder. In the case of national mining companies and societies, the monitoring program is performed with funds from the State budget, ordered by the Ministry of Finances and its specialized directorates.

3.1. Case studies for Current Status of Closure Processes and Applied Remediation

One of the representative mining areas is located in the Banat region, at Moldova Nouă. The copper ore that can be extracted at Moldova Nouă represents 30% of the copper reserves of Romania. The porphyry copper deposit is estimated at around 500 Mt with an average grade of 0.35% Cu [65].

Copper is an essential element for the nutrition of plants and animals, in small quantities stimulating growth, but it is poisonous in large quantities. During alteration and sedimentation, copper sulphides are easily oxidizable, turning into oxides and sulphates, and copper turns into mobile copper in solution. Copper can precipitate in environments with high pH, generating enrichments in the cementation zone, in the form of chalcozine and chalcopyrite. The amount of copper remaining in the solution is captured in the hydrolysed sediments through adsorption phenomena.

The copper extraction posed numerous environmental problems caused by the dust coming from the waste dumps, which was blown by the strong winds (reaching sometimes 120 km/h) event toward the neighbouring country (Serbia), by the acid mine drainage and contamination of the soil and Danube River with heavy metals (Zn and Ni). Over 30 years of ore extraction and processing led to the occurrence of three large tailings lakes (with a total area of 306 ha), which represent a big pollution source in the zone.

In a study carried out in 2009 [66], the measurements performed in the mining perimeter pointed out high concentrations of heavy metals in the waste heaps, and lower levels in the tailing ponds, except for copper (Cu), which is present everywhere well above the normal limit of 20 ppm from the Order No. 756 [67]. The effect of heavy metal pollution, deposited by airborne suspensions, is felt in soils located as far as 2 km from the mining area, with values exceeding the intervention threshold for sensitive crops for Cr, Cu, Mo, Ni, Pb, and Cd. The impact of dust and sulphur dioxide (SO_2) on the air is insignificant, except on windy days, which disperses dust from the tailing pond.

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Figure 5. Moldova Nouă – dump.

Figure 6. Moldova Nouă – quarry.

Another case study is in Suceava County, in northern Bucovina: the ponds Tărnicioara, Valea Straja, Poarta veche, Dealul Negru, Pârâul Cailor, active until 2006, have generated mining waste from ore processing at the Fundu Moldovei and Leşu Ursului mining sites.

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Figure 7. Târgu Lăpuș waste pond from Maramureș county, where the dam stability and environmental problems have occurred decades after depositing the mining waste.

These waste materials resulted from the deposition of liquid waste derived from barite ore processing from the Ostra barite deposit onto the three ponds within the Tarnița perimeter. Meanwhile, the ponds within the Fundu Moldovei area are influenced by the deposition of waste materials from the nearby extraction of limestone and dolomite. Literature studies reveal the presence of major elements such as As, Ba, Cd, Co, Cr, Cu, Mo, Ni, Pb, Sb, and phenols, indicating the existence of aluminosilicate minerals and iron sulphides. Pyrite, the most commonly encountered mineral in mining waste, is responsible for generating acid drainage [68–70].

The third case, in Maramureș county, highlights the environmental problems of the ponds at Târgu Lăpuș. The ponds are composed of settled solids and free water, from the waste itself and supplemented by inflowing groundwater and direct precipitations. Part of the free water remains in the supernatant pond and was removed by evaporation during long-term exposure, depending on the local weathering processes. The excess free water, decanted and drained from the pond, was lost by underground infiltration or discharged into nearby surface receiving water bodies, without any treatment (Figure 7). At this location, the global contamination of water systems is one of the critical environmental-related issues associated with increased industrialization, natural and mineral resource exploitation [71].

3.2. The National and International Legislative Framework

Mining operations are inherently associated with environmental impacts and effects on human health, spanning from the exploration phase to closure and post-closure activities. Environmental concerns within the mining industry necessitate a systematic approach built upon the knowledge acquired from regions with long mining traditions and better environmental performance in the world. Viable environmental management techniques have been applied to exploited areas within Romania. Internationally, guidelines, regulations, and procedural codes have emerged, particularly from the 1990's onward, outlining the fundamental principles of environmental management in the mining sector. In Romania, the Environmental Protection Law no. 137/1995 establishes the principles and strategic elements that ensure sustainable development [72].

The main legislative components pertaining to environmental protection are: the Environmental Protection Law, the Water Law, and the Mining Law. The Mining Law 85/2003 regulates all mining activities in Romania. The Ministry of Economy, Trade, and Business Environment (MECMA) holds the responsibility for strategic planning and policy development concerning the mining sector [40]. However, the competent authority for implementing the provisions of the Mining Law is the National Agency for Mineral Resources. The primary focus of the Mining Law is directed towards the management of exploration and exploitation activities.

Mining activities are subject to a national legal framework harmonized with the European one, which regulates the opening, operation, and post-mine closure activities to ensure minimal disruption to the environment.

The necessary study for opening a mining operation is conducted in accordance with Government Decision No. 1,213/2006, which establishes the framework procedures for assessing the environmental impact of specific public and private projects [73].

The management of waste generated from mining activities is regulated by Government Decision No. 445/2000 [74], which outlines procedures for both surface and underground quarries and mines, as well as the storage of overburden and impoverished materials. Mining operations generate waste during excavation, physical and chemical processing for concentrate production, and ore stripping. The management and tracking of this waste are governed by Decision No. 856 of August 16, 2002 [75], also by the Extractive Waste Directive (EWD; Directive, 2006/21/EC) and the Best Available Techniques Reference Document for the Management of Waste from Extractive Industries, in accordance with Directive 2006/21/EC – MWEI BREF (review of the Reference Document for Management of Tailings and Waste-Rock in Mining Activities - MTWR BREF) [76].

Water management is a top priority in mining activities due to the leachate resulting from washing impoverished or overburden geological material, residual waters from chemical processing of mining concentrates, runoff from heaps, and pumped groundwater, all of which is ultimately discharged into surface waters. Indirect discharge through soil is also possible, especially after mine closures. Therefore, the legislative framework governing mining activities also encompasses the protection of groundwaters and surface waters [77–79].

The management of soil in mining activities is regulated by Government Decision No. 756/1997, which establishes the maximum permissible values for hazardous substances resulting from mining activities [67].

Assessment of the data available at EU level shows that even with a series of EU regulations and guidelines in place, the available reports are still not coherent and sufficient enough from the point of view of its scope [16].

3.3. The Existing Best Practices in the Mining Sector

The subject of successful mine closure holds significant importance for all parties in-volved:

- For mining companies, it addresses the reduction of environmental, social, and security risks in the area, as well as ensuring the necessary funds for site rehabilitation. These actions are detailed explained [76,81] and correspond to Generic Best Available Technics (BAT) on corporate management, including necessity of the extractive waste characterization, identification of extractive waste site and management options, Environmental Risk and Impact Evaluation and waste hierarchy;
- For authorities and the government, it addresses acute environmental issues and contributes to the social and economic revitalization of extensive regions.
- For communities, it helps avoid local economic and social collapse.

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In terms of environmental factors' quality, pollution and sometimes irreversible degradation resulting from mining activities provide strong arguments for the implementation of correct ecological restoration standards and policies [67,82].

Embracing best practices in mining entails the adoption of environmental management by mining companies, as well as good practices concerning communication with the local community, accident prevention, transparent decision-making, annual report publications made accessible to the public, continuous social dialogue, adoption of the latest technologies, and collaboration with research and development sectors and relevant universities.

In the BAT there are also included mitigation and safety measures to ensure the short-term and long-term structural stability of the extractive waste deposition areas, and the physical and chemical stability of extractive waste. Other measures are intended for preventing or minimizing water status deterioration, air and soil pollution or other risks to human health, flora and fauna, related to noise emissions, odour nuisance and visual impacts [81].

The investments in extractive activities need to protect the environment and human health, to avoid the supplemental costs of remediations and potential accidents, which could be many times higher than the prevention costs. Proper planning, design and operation are imperative to avoid clean-up and remediation costs due to Extractive Waste Facilities failures. This aims to enhance performance standards and ensure that initiated projects and investments have the least possible impact on the environment.

The EC and Member States discuss environmental issues in relationship with the management of mineral wastes from the mining industry and analyse the applicability of both emerging and established techniques to their management. Addressing in deep the relevant issue of mineral waste management could help improve practices in the mining industry, as well as gathering data intended for mining operators, researchers and academics interested in mineral waste management.

3.4. Heavy Metals Content in Surface Waters caused by Mining Activities

In Romania, the situation of heavy metal pollution for the year 2022 [83] (Table 4) shows that the sectors of activity with significant contributions to total heavy metal discharges in wastewater are: i) domestic wastewater collection and treatment; ii) chemical production; iii) mining industry; iv) metallurgical industry/metal construction [84]. Taking into account only the contribution of the mining industry, it can be seen that the heavy metals found in the surface waters in Romania are: arsenic, copper, lead and zinc.

Table 4. The situation of surface water heavy metals loadings and the percent estimated to be caused by the mining industry**.**

Metal	Hydrographic basin	Quantity (%)	Total (tonnes) in Romania	Mining Industry contribution to the total (%)
As	Mureș River	89.76	0.025	90.67
Cu	Mureș River	78.43	39.69	78.68
Pb	Argeș River	38.40	1.46	1.17
	Mureș River	32.17		
	Bega-Timiș Rivers	8.69		
Zn	Argeș River	32.77	85.62	23.28
	Mures River	23.18		
	Siret River	17.31		

The share of mining industry for Pb pollution is 1.17%, smaller than that given by the industries of urban wastewater collection and purification (87.99%), and production and supply of electricity, heat and hot water (9.42%). Zinc pollution mainly come from urban wastewater collection and purification (64.87%), the mining industry (23.28%), and metallurgy/construction of metal structures (10.39%).

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It should be mentioned that Mureș River crosses both Alba and Hunedoara counties, where Figure 3 indicates the operating open cast mines (Roșia Poieni and Roșia Montana), while Siret River collects tributaries from Suceava county.

Another conclusion would be that mining is not always the main source of pollution with heavy metals in surface waters, important contributions also being brought by other industrial or domestic sources.

3.5. Effects of Pollutants on the Environment

Mining waste consists of mining waste rock, processing waste, traces of variously sized ores, diverse compositions, and often potentially hazardous substances. These deposits represent a continuous source of environmental pollution in the studied region, as well as a potential source of risk for both the environment and the human communities in the area.

The impact of waste rock heaps on the environment occurs throughout the entire life cycle of these deposits: before, during, and after the actual mining operations. The impact on the land includes the removal of vegetation, the construction of access roads and necessary infrastructure, the occupation of land with large quantities of waste rock resulting from ore processing activities, deposition in heaps and tailings ponds, excessive water resource usage leading to excess acid water generation, destruction of natural habitats, and pollutant emissions in various forms into the surrounding ecosystem.

Monitoring of environmental factors in closed mining areas involves tracking the evolution of air quality and meteorological conditions, the quality of water discharged from the mining area and the receiving water bodies, acid runoff from the mine, soil and vegetation quality, noise and vibration levels during closure and rehabilitation works, stability and condition of land surfaces within waste rock deposits (tailings ponds, waste rock heaps).

Mining waste deposits can also contribute to atmospheric pollution, especially during longer dry periods when fine particles can be carried by the wind and transported to the surrounding area. Revegetation of the excavations and waste dumps helps to limit this type of pollution toward an insignificant impact.

4. Discussion

Mining activity brings about profound modifications to the components of the environment. Human activity, as a morphogenetic agent, has become the most significant factor in shaping the landscape. Soil contamination with heavy metals has become a growing concern due to their persistence and environmental toxicity, with impacts on human health and the environment. Soil remediation is a crucial process to help safeguard the environment and human health.

A soil remediation technique known as soil replacement reduces pollutant concentrations to an acceptable natural limit. Soil spading and soil replacement are two methods used in soil remediation to mitigate the effects of soil contamination by heavy metals or other pollutants. Soil spading, also known as soil turnover or soil cultivation, involves digging and mixing the polluted soil with clean soil to decrease contaminant concentrations. This method is often employed for large areas of contaminated soil, where removing and replacing the entire contaminated soil layer is unfeasible. Soil spading aids in soil aeration and promotes microbial activity, which can accelerate the natural breakdown of contaminants in the soil.

4.1. Heavy Metal Pollution Remediation Strategy

Recommendations for ecological restoration of an area require the assessment of the natural background, as often in mining areas where mineral resources are found at various depths, minerals may appear as outcrops on the surface, potentially leading to elevated background values of certain substances in the environment.

Under these circumstances, ecological restoration and/or depollution of a site may not be achievable at the parameters set by current legislation if they are more stringent than the natural characteristics of the surrounding environment in that area.

4.2. Closure and Ecological Reconstruction Procedures Implemented

The use of systematic management procedures can be a powerful instrument of controlling the environmental impact in the mining sector.

In the execution phase of closure and ecological reconstruction of the mines the following works should be done:

i) Monthly monitoring program including: monitoring the quality of discharged water and watercourses, as well as discharge points where temporary impacts from the works are likely; monitoring sediment in watercourses and discharge points where temporary impacts from the works are likely; monitoring the stability of terrain and landfills where temporary impacts from the works are likely.

ii) Daily monitoring program including: noise and vibrations resulting from remediation operations, groundwater level in processing residues in case of automated recording.

The closure plan outlines the vision for the final outcome of the process and establishes specific objectives for implementing that vision. The closure plan should also encompass considerations such as counselling for mine personnel regarding re-employment options during the period leading up to cessation of activities.

In the warranty and post-closure phase of the mines, the final monitoring scheme for post-closure should be developed based on the results of monitoring during the pre-closure and ecological restoration phases. As a general rule, this monitoring scheme will be simpler and less frequent compared to the one in the pre-closure phase.

4.3. Strategies for Anthropogenic Relief Rehabilitation

Rehabilitation entails not only restoring the previous state but also introducing new forms and ecosystems, and the existence of valuable biotopes in areas with mining activities being the subject of numerous studies [85].

The recent decades brought an intensification of anthropogenic influences, which give rise to a new morphology characterized by relief inversions, as well as a restructuring and rearrangement of dislocated materials.

Impact and risk assessment represents an effective strategy to address environmental quality concerns and to identify local, regional, and national priorities. Ecological impact assessment is crucial for the process of remediation and ecological reconstruction, forming the basis of management practices.

Phytoremediation is a cost-effective and ecologically sound approach that can be used alone or in conjunction with other remediation techniques. However, phytoremediation may lead to contaminated biomass, which requires proper disposal to prevent further environmental pollution. Potential environmental impacts of both the phytoremediation process itself and the disposal of resulting contaminated biomass must be considered.

While phytoremediation is a successful and efficient strategy for removing pollutants from the environment, it does have limitations and disadvantages that are not fully understood due to limited exploration and research done mainly in controlled environments.

If soil toxin levels are too high, this can affect plant growth and the ability to remediate the site. Additionally, certain plant species may be more suitable for specific types of contamination than others, and selecting the wrong plant species could result in lower phytoremediation efficiency. Moreover, there's a risk of increased contaminant uptake by plants, which could pose potential health risks if consumed by animals or humans. Finally, the economic feasibility of phytoremediation could be limiting due to associated costs of plant cultivation, monitoring, maintenance and proper disposal of contaminated biomass.

5. Conclusions

On one hand, it is impossible for the humanity to continue its actual living standards and cope with the new technological challenges without mining. All the new technologies, including those related to renewable energies, require components that can be obtained only from mineral resources. On the other hand, for the benefit of humankind, the mining operations should be carried out with the utmost care, in order to disturb as little as possible the environment and not to cause harm to human health. However, some disturbances will always happen, given the nature of the process.

From all the available data studied for this paper it resulted that there are still environmental problems in the areas of closed and remediated mines of the six studied counties. This observation could be extended in Romania to the rest of the counties.

Monitoring the closed mines and the discharges of active mines should be carried out regularly, and the results made publicly available, because often it is very difficult to find relevant data on this issue.

The referenced materials show that mining is not always the main source of pollution with heavy metals in surface waters, important contributions also being brought by other industrial or domestic sources.

In mining areas where mineral resources are found at various depths, minerals may appear as outcrops on the surface, potentially leading to elevated background values of certain substances in the environment. Under these circumstances, ecological restoration of a site may not be achievable or sustainable at the parameters set by the current legislation, if they are more stringent than the natural characteristics of the surrounding area.

This study concludes that the mining sector in Romania, although it has the necessary techniques and technologies for the ecological rehabilitation of degraded lands related to the Extractive Waste Facilities and the elimination of negative impacts on the environment and public health, has not yet been able to fully concretize its remediation efforts.

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