Integrated Environmental Assessment and Management — Volume 19, Number 4—pp. 949–960
Received: 22 March 2022 | Revised: 3 March 2023 | Accepted: 7 March 2023

Special Series

Uncharted risk measures for the management of sustainable mining

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EDITOR'S NOTE:

This article is part of the special series "Remtech Europe 2021: International Approaches to Contamination Management." The series documents and advances the current state of the practice with respect to the sustainable management of contaminated sites, high-resolution techniques for characterization, disrupting technologies for remediation of soil and groundwater, and risk assessment frameworks.

Abstract

Governments commit to ensuring the welfare of their citizens by drafting and enforcing regulations that ultimately ensure the sustainability of mining. This study contributes to improving the sustainability of mining throughout the mine's lifecycle until the final destination of the mining products. We propose recommendations that address the sustainability of mining from a global perspective, framed around the United Nations Sustainable Development Goals (SDGs), following waste hierarchy with Common Agricultural Policies, and policies from the Green Deal on climate, energy, transport, and taxation. Tailings are the most significant source of environmental impact in mining operations and, therefore, must comply with controlling regulations through Tailings Management Facilities (TMFs). However, there have been several mining accidents involving TMFs worldwide. The recommendations begin during planning, preconstruction, and construction with practices such as fair consultations, tax revenue fairness, and mandatory insurance. The operation and management support parallel industries to mining and supporting health and education. Emergency planning involves the surrounding communities in mock drills and environmental monitoring. In the closure and rehabilitation, remediation technologies such as phytoremediation, carbon sequestration incentives, and biomass valorization are recommended. Finally, supporting a circular economy by prioritizing ethical consumption, resource reduction, material recovery, and replacing toxic minerals and materials from the start with "benign by design" is recommended. The strategies involve stakeholders directly or indirectly related to the mining companies' contamination and demonstrate a commitment to the SDGs, offering a holistic perspective on scientific, social, and regulatory issues. *Integr Environ Assess Manag* 2023;19:949–960. © 2023 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Biomass valorization; Community involvement; Mining; Risk management; Tailing Mining Facilities

INTRODUCTION

Minerals have a long association with humankind in their day-to-day activities. They also have cultural value as they have played a crucial part in advancing civilization. It is often difficult for the consumer to visualize the whole life cycle of a product and the importance of mining in high-tech and everyday products. For instance, food crops are harvested and processed with tools and machinery made from minerals; water is purified and transported through metal or plastic pipes; furniture in our homes is made from metals, plastics, and materials derived from petroleum products; and energy is produced and transported by structures made of metal. All of these things require the extraction of mineral resources.

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Published 27 March 2023 on wileyonlinelibrary.com/journal/ieam.

 DOI: 10.1002/ieam.4769

On the other hand, mining causes contamination, drought, land degradation, deforestation, and biodiversity loss, which jeopardizes food security by reducing soil quality. Displacement of some Indigenous and rural communities is a major social issue. Moreover, mining can make a region socially unsafe and create disturbances by generating violence and unrest (Contreras et al., 2020; Owen et al., 2020; Zarsky & Stanley, 2013).

Planning preconstruction and construction

Besides active mines, abandoned mines are also a significant threat to health as direct exposure to acid mine drainage discharged from abandoned metal mines can affect aquatic biota and human health (Tomiyama & Igarashi, 2022). Since minerals play a vital role in many areas, they cannot be entirely avoided. The only option to maintain a balance between sustainability and mining is to make the life cycle of mining as sustainable as possible. This includes prioritizing sustainable mining practices.

The recommendations proposed in this work are aligned with the United Nations Sustainable Development Goals (SDGs; Table 1) and with the Common Agricultural Policies (CAPs) of the European Commission (Pe'Er et al., 2019). Common Agricultural Policy supports farm income and resilience to enhance food security, foster green growth, mitigateand adapt to climate change and sustainable energy, and promote business development and inclusion in rural areas (Pe'Er et al., 2019).

Financial flows from mineral expenditures have no significant impact on community welfare, as shown by several studies (Fröberg & Waris, 2011; Kar & Curcio, 2011; Zarsky & Stanley, 2013). On conflict minerals, European law on international responsible sourcing standards was enforced as of January 2021, which aimed at stopping international trade to and from Europe of minerals associated with armed conflict and forced labor (European Commission, 2020).

Construction and implementation of regulations

Countries with well-established mining industries, such as Canada, Australia, and South Africa, are also the ones that own the most extensive mining industries, and governments have used their guidelines on good practices for writing their policies for the prevention of failures on Tailings Management Facilities (TMFs) (Tailings info, 2018). The United Nations Office draws policies and plans for Disaster Risk Reduction (UNDRR, 2022), which can be associated with TMFs. The Sendai Framework for Disaster Risk Reduction 2015–2030 outlines seven clear targets and four priorities for action to prevent new and reduce existing disaster risks. Consequently, 17 SDGs were established to support the 2030 Agenda for SDG implementation. The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at COP21 in Paris on 12 December 2015.

Challenges in consistent implementation

Consistent implementation of these regulations during the whole life cycle of a mine is a challenging job. Goldcorp, for instance, was qualified as outstanding on the Jantzi Social Index in 2008 for its censure toward highly conflicted areas, but later was ineligible for socially responsible investing portfolios the same year (Jantzi Research, 2008).

TABLE 1 Sustainable Development Goals (SDGs) and their relevance in mining

SDG	Relevance to mining.
SDG 1 & 2	Seeks to end poverty by supporting parallel industries, mainly farming, with insurance instruments.
SDG 3 & 4	Support health and education.
SDG 6	Promotes reducing water pollution and scarcity in the case of an accident.
SDG 7	Encourages energy efficiency by improving extraction and smelting techniques; promotes CO_2 emission reduction.
SDG 8	Promotes growth and decent work for the surrounding mining and/or farming communities so that inequality can be reduced.
SDG 10	Encourages official development assistance, tax fairness, and insurance so that financial flows get redistributed.
SDG 11	Ensures that essential services make settlements resilient and sustainable as risk management, but not only in the case of an accident.
SDG 12	Promotes sustainable consumption and production patterns by encouraging resource efficiency, environmental sound management of chemicals and wastes, benign design, and maximum resource extraction.
SDG 13	Action to combat climate change by a long-term remediation plan that incorporates carbon into the soil and immobilizes and/or transforms toxic effluents.
SDG 14	Encourages reducing toxic effluents and decreasing ocean acidification.
SDG 15	Fosters sustainable use of terrestrial ecosystems.
SDG 16	Campaign for fair trade in the mineral industry to reduce violence, abuse, and exploitation from suppliers' countries.

Source: UNDP (2016).

Recommendations for sustainable mining: Balancing social, environmental, and economic dimensions

The mining industry must reflect on social and environmental investment to reach a sustainable status. Unfortunately, reclamation of the waste from mining poses few economic incentives; therefore, it is essential to make an alliance between the environmental, social, and economic dimensions to facilitate sustainable growth. The recommendations that we propose here consider the SDGs, waste hierarchy, the CAP, and the Green Deal (a set of policy measures that targets the European Union to achieve climate neutrality).

This article proposes a long-term risk management plan for reducing and mitigating the damage caused by mining accidents, with specific, measurable, achievable, relevant, and time-bounded targets. The present work is an overview of past incidents regarding TMFs and the measures taken by the European Union (EU) to manage the risk and prevent further incidents. Furthermore, a brief discussion of some innovative and practical recommendations is provided to improve waste management throughout the entire life cycle of a mine, including ethical consumption and circular economy relevant to the mining sector. All these suggestions proposed as preventive steps would mitigate the impact of regular mining operations during the entire life cycle of the site and reduce the effects of a significant accident.

Literature review

A brief history of accidents and contingency measures. In Europe, around 60% of soil-contaminated sites are estimated to be caused by mineral and heavy metal waste, as reported by the European Commission (Panagos et al., 2013). The European Commission has created a series of documents, namely, the Best Available Techniques Reference Document (BREF) for the Management of Tailings and Waste-rock in mining Activities (MTWR) (MWEI BREF, 2018). The document presents the up-to-date and best available techniques that can be used to manage TMFs, which pose an environmental and human concern for the EU, including accidents. The Guidance Document for Risk Assessment Pre-selection Protocol for the Inventory of Closed Waste Facilities mentions specific steps for the preselection of wastes based on article 20 of Directive 2006/21/EC. The document also addresses measures for rehabilitation and/or remediation of active and/or abandoned mines, including tailings (Stanley et al., 2011).

The MWEI BREF document (2018) addresses almost all questions related to mining and its possible effects on living organisms, offering specific questions that can be used for mine risk assessment. A series of surveys were conducted by the industry to estimate the amount of total waste, pollutants, and water use in the EU. The industry surveys revealed that certain sectors, such as oil and gas extractive waste, had minimal or no water use due to their complete water recycling, while other sectors had undisclosed data on water use. It seems necessary to consider that the data on the use and quality of water and soil were reported voluntarily by the mining sector. The MWEI BREF document (2018) reported an investigation of 18.401 mine sites and 218 tailings dam accidents that identified the leading causes of dam failure as unusual weather, poor management of the facilities, or seepage. Less frequent causes were slope instability or structural defects.

According to MWEI BREF (2018), there were six accidents in Europe related to upstream-raised dams and seven accidents related to downstream embankment dams, while the numbers at the global level were 60 and 10, respectively. In Brazil, the upstream embankment method was prohibited by 1993; however, in 2012, this prohibition no longer existed in the legislation (Carmo et al., 2017).

Important accidents related to mining. After this change, some accidents occurred. One of the most important was the Bento Rodriguez dam rupture in Minas Gerais in November 2015 (Zago et al., 2019). In January 2019, a massive accident occurred in the Córrego do Feijão mine in Brumadinho. This last upstream embankment incident killed 250 people and damaged the ecosystem (National Geographic, 2019). After that disaster, Brazil's legislation was changed by decommissioning the upstream dam. However, the deadlines were extended by August 2019 (Mining, 2019).

Supporting Information: Table S1 presents some incidents related to TMFs in Europe during the last 30 years. These accidents produced casualties, injured people, and caused ecosystem damage, contamination, economic loss, and social unrest. Human errors mainly caused the sludge tailings spill. For example, in Baia Mare, Romania, in 2000, an environmental disaster occurred when 100 000 m^3 of cyanide-laced water spilled from a TMF into three Balkan rivers and the Danube. The United Nations Economic Commission for Europe (UNECE) encourages economic cooperation among its Member States. Afterward, the UNECE member countries decided to jointly develop safety guidelines and good practices for TMFs under two UNECE Conventions: the Convention on the Transboundary Effects of Industrial Accidents (Industrial Accidents Convention) and the Convention on the protection and use of Transboundary Watercourses and International Lakes (Water Convention) (UNECE, 2014).

Measures to improve the safety of TMFs—Guidelines and checklist for competent authorities. The development of guidelines and a checklist for improving the safety of TMFs serves as a methodology toolkit for the expert authority to reduce the number of accidents and mitigate their effects. Ultimately, it is the local government's responsibility to write, abide by, regulate, and comply with these guidelines.

Winkelmann-Oei et al. (2015) explained this toolkit methodology as consisting of a checklist for compliance with existing best practices guidelines by UNECE and the Tailing Hazard Index (THI). The THI indicates the degree of hazard presented by a TMF, taking into consideration several impacts; these include (1) the capacity of the dam;

(2) the toxicity of the tailings; (3) the quality of the management; (4) the natural conditions specific to the site; and (5) dam safety. The higher the THI, the greater the risk of a possible accident's impact on the TMF. The UNECE Convention on the Transboundary Effects of Industrial Accidents (UNECE, 2014) provides the legal basis for preventing industrial accidents and strengthens international cooperation. It considers the best-known practices of TMFs and proposes to implement them through the guideline check and categorization of THI. Additionally, the convention advocates for public consultation with neighboring communities before the start of a mining project to reassure them about the utilization of best practices and subsequent validation of the plans, mapping critical TMFs, and categorizing them according to the degree of hazardousness (i.e., THI), as well as the training of the operators and authorities in case of TMF accident.

Finally, several proposals to contribute to mining sustainability are also considered, especially to avoid incidents or at least mitigate their effects. In general, it is to improve the sustainability of mining from extraction to the end of the mineral's life.

MATERIALS AND METHODS

This article provides an overview of the gaps in countries' governments' regulations on mining activities.

To develop this document, we followed a comprehensive methodology that involved several key components. First, we conducted a critical review of the official literature on Best Management Practices for Minerals from Europe, Australia, and Canada, in addition to analyzing gray documentation sourced from the industry's risk management self-evaluation. Second, we actively participated in soil pollution meetings and engaged in discussions with international experts. Third, we revised current news and interacted with the community to stay updated on recent developments related to accidents in the TMF.

Based on our findings, we identified gaps and made recommendations not only on policies relevant to the management of the TMF but also on the entire life cycle of a mine. The ultimate goal was to improve the overall management of minerals, from extraction to disposal, while prioritizing safety and sustainability. The 17 SDGs, CPA, and the European Green Deal were revisited in relation to mining, and recommendations were developed (Figure 1).

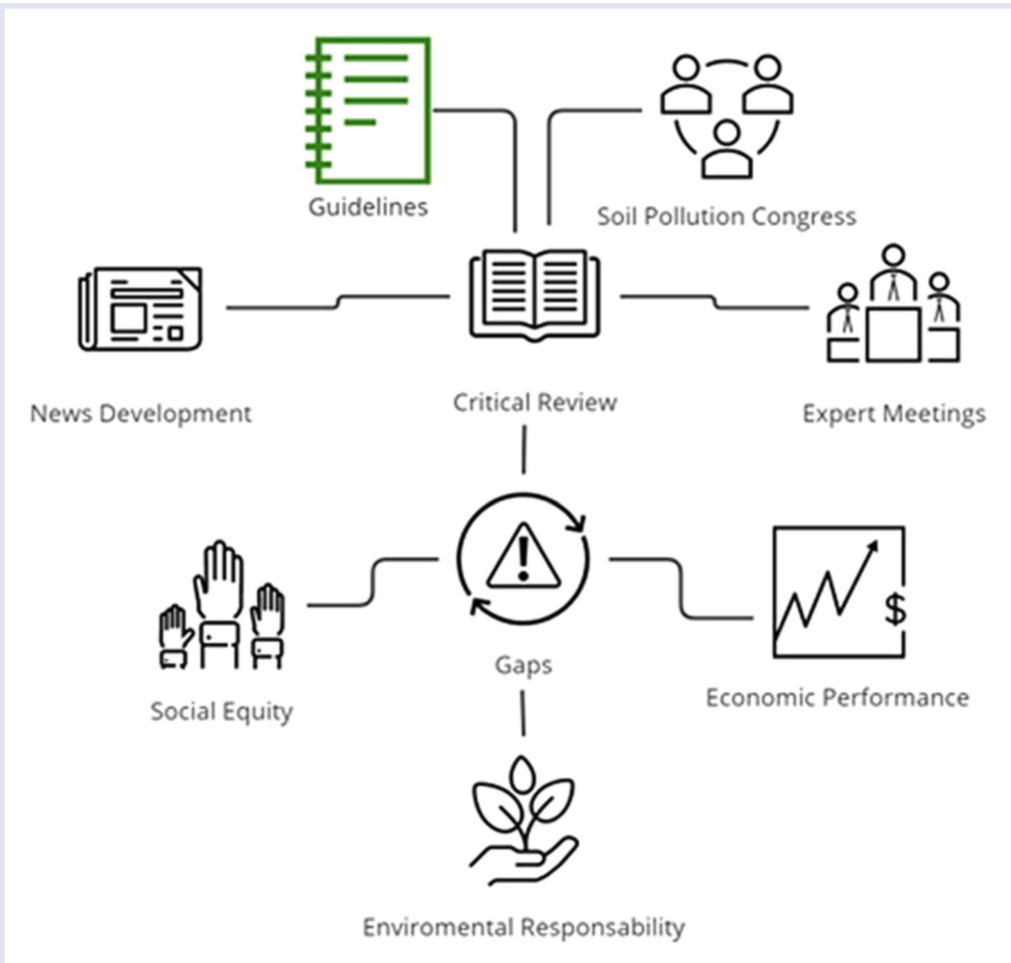

FIGURE 1 Methodology present in the study

The materials considered here are referenced accordingly throughout the article. Additionally, study cases for phytoremediation are shared by the authors' research data. Different levels of implementation are addressed to mining companies, local and international governments, raw material and product traders, smelters, refiners, and nongovernmental organizations (NGOs).

The research findings are framed in the context of the current scientific discussion involving the necessity of improving the regulations on mining that comply with the SDGs, strengthened CAPs, and the circular economy. The research strategy for this assessment consisted of online and library research on legal, political, economic, and societal considerations of pollution and disaster occurrence by mining activities.

RESULTS AND DISCUSSION

Sustainable practices need to be implemented throughout the life cycle of a mine. Practices will be discussed below in detail and are necessary as risk-prevention measures so that the impact would be minimal in case of a disaster. Necessary measures such as proper site design, environmental assessment, and proper infrastructure at the design and construction phase are critical to helping reduce the risk and scale of any impacts in later accidents. We discuss in this work the underrated "Uncharted measures," which are not customarily addressed in the mining narrative. The following are the recommendations to include in the guidelines and good practices to make mining as sustainable as possible.

Mining waste management processes may involve dewatering by geotextile tubes, anaerobic wetlands, reverse osmosis, biological farming, passivation, microencapsulation and biological treatment, use of microbial mats or algae, and so forth (Garbarino et al., 2018). Managing waste with biological and phytomanagement methods is socially acceptable, environmentally desirable, and economically viable (Conesa et al., 2012). Based on our expertise and literature review, the physicochemical and biological characterization of the ecosystem (soil, water, and biota) is necessary. Depending on the THI, the exact methodology can be designed. In parallel, an evaluation of the relevant plants that would serve as hyperaccumulators of toxic substances for site remediation should be undertaken.

Ultimately, the objective of the recommendations proposed in this study is to challenge the paradigm of the "polluter pays" principle in exchange for planning for risk prevention and reclamation from the start with preventive measures involving environmental goals yet economically interesting to be implemented by the mining companies.

Local governments, miners, smelters, farmers, local communities, and other stakeholders must check the sustainability of their mining enterprises. Technical and already put-in-place guidelines can be found in the guidelines implemented by the UNECE (Vijgen & Nikolaieva, 2016). Table 2 presents a summary of our recommendations.

Planning, preconstruction, and construction

Fair consent. At the start of the life cycle of a mine, the local population affected should be consulted so that they are informed but do not necessarily have the power to veto them. Sometimes, negotiations that are not entirely transparent result in the approval of the mine without the consent of the local population. Actually, several financial institutions, including the World Bank, have pushed for the concept of consultation over consent. Therefore, free, prior, and informed consent should be implemented (MacInnes et al., 2017). Despite the economic benefits of mining, social disruption cannot be fully offset, even with accurate cost accounting. The number of assassinated community leaders is alarming in Latin America and around the world, mostly in impoverished countries, as noted by Globalwitness (2018) in their report. Many of these social leaders are environmental defenders. More substantial punishment should be meted out to the culprits to serve as a deterrent to others or intended violators, as well as fair trade and mapping original minerals; see section on Ethical consumption.

Tax revenue fairness. Companies transport unrefined ore to another country with lower refining costs to reduce the tax they have to pay in the original region. In some cases, this transport is only documented on paper and directed towards a tax haven, enabling these companies to avoid paying taxes altogether. (NSSRA, 2017). This could be avoided if all the governments would force companies to pay a tax in every country where the parent or subsidiary company operates, which requires fair payment to the country from which the ores originate.

Companies' shares have no limit (Hinton, 2020) and should be illegal while half of the world's population lives in poverty (Agarwal et al., 2007). Companies involved in extracting natural resources should pay their taxes to local governments and, ultimately, to local communities. This is already changing; in May 2018, it was announced that British Columbia and the Nisga'a Nation (Indigenous communities near the mining site) were the first to receive a share of the gold mines' tax revenue (Ruiz Leotaud, 2018).

Perhaps, a hindrance to implementing this fairness in the local policies is the influence of the mining corporations. Employees of such corporations work later on for the government and vice versa, influencing policy decisions. A more detailed study can be found in Vélez-Torres and Ruiz-Torres (2015).

Mandatory insurance. Local governments are responsible for writing laws that allow the protection of the population, environment, and goods. Therefore, local legislative enforcement is required, including creating a budget for potential accidents by obtaining mandatory insurance. The Brazilian government claimed US $40 billion for compensation to the mining company Samarco for the damages caused by the Bento Rodrigues dam failure (Phillips, 2018). After some significant mining disasters, the mining companies failed to compensate the affected populations on time;

TABLE 2 High-risk impacts to be addressed by measures for sustainable mining operations

Issue to address	Measures to be taken
Planning, preconstruction, and construction	
Problematic consultations	*Fair consent*: Free, prior, and informed consent to ensure transparency in mining practices.
Tax revenue that is not reflected in local communities' well-being.	*Tax revenue fairness*: Companies pay a fair tax contribution in every country in which the parent or subsidiary companies operate.
In many cases, insurance is not in place, and a contingency plan is compromised for a deficit of monetary resources.	*Mandatory insurance*: Companies must have mandatory insurance or a protection instrument such as captive insurance.
Operation and management	
Mining monopolizes economic activity, and the region is depressed after the closure of the mine.	*Supporting parallel industries to mining*: Companies should support other parallel industries and/or services.
Basic services missing	*Supporting health and education*: Ensure basic services during operation.
There is overconsumption that is beyond the carrying capacity of the environment.	*Ethical consumption*: Promoting consumption reduction, recycling, and reuse.
Many mining operations are in regions where human rights are violated.	Fairtrade practices and mapping the origin of minerals.
High-tech devices are planned to have a short life span for the sake of economic incentives.	Abolishing planned obsolescence.
The occurrence of minerals has a limit, and overexploitation causes the reserves to become exhausted.	*Waste as a resource*: Ensuring maximum mineral and material extraction and utilization to support a circular economy.
When the THI is very high and/orthe substances are included in the REACH list, the danger that poses substances or mineral in the mining operation override the benefits.	*Replacing toxic minerals*: Toxic minerals and materials must be replaced and, better yet, designed to be benign from the start.
Emergency planning	
High-risk impact due to accidents could occur through physical contact and toxic contamination. If the communities are not aware of the dangers, they cannot react in case of an emergency.	*Mock drills*: The community must be involved in the preparation and mock drills of possible accidents.
Community members close to the sites have no way to alert and warn the other stakeholders about danger signals or action levels of contaminants.	*Environmental monitoring*: The educated and involved community should be provided with communication alarms and monitoring kits and/or biological markers.
High-risk impact due to resource scarcity.	*Ensuring basic services* during and after a disaster.
Closure and rehabilitation	
The pollution caused by mining accidents endangers a whole ecosystem and the services it provides. It presents the potential presence of hazardous materials and compromises the rehabilitation of the surrounding areas.	*Phytomanagement*: A long-term reclamation and rehabilitation planto be implemented from the operational phase of a mine. For this, it is expected that the companies join in the research on the appropriate strategies for their type of hazards.
Mining operations deplete organic carbon reserves from the soil, use energy, and release CO_2 during operations.	*Carbon sequestration incentives*: Mining operations may encourage the building of natural reserves for carbon sequestration by using remediation technologies.
There are not many incentives for phytoremediation.	*Biomass valorization*: Provides an economical incentive for phytoremediation.
Accidents from TMF spill to nearby terrains.	A life barrier of perennial trees surrounding vulnerable sites of a mine or TMF should be encouraged as a risk-prevention measure to mitigate the damage.

Abbreviations: REACH, Registration, Evaluation, Authorization, and Restriction of Chemicals; THI, Tailing Hazard Index; TMF, Tailings Management Facility.

for instance, after the disaster of Minas Gerais (November 2015) in Brazil, the company battled legal lawsuits until a final settlement in November 2018. This could have been avoided if an insurance policy had been in place.

Meanwhile, the lives of those affected are on hold while they await Brazilian legal decisions. The Renova Foundation, responsible for repairing the damage caused by the Samarco dam in Minas Gerais, Brazil, has already spent over US $2 billion, but has yet to take significant actions towards restoring the Doce River Basin affected by the disaster. In this way, the Public Prosecutor's Office asked for Renova's extinction (Souza et al., 2021). It would be necessary for the mining companies to develop strategies to join forces and produce an alternative instrument that allows them to create insurance or funds such as "captives," which means self-insurance for mining companies and will represent the miners' and communities' security going forward. Ultimately, this is a way to protect taxpayers' money, employees and surrounding communities, and the company's and government's reputations.

Similar instruments had been regulated by the EU (Scannell, 2012). Indeed, it has been reported that companies with captives have higher profitability, more significant market share, lower sales volatility, and lower cash balances (Bodnaruk et al., 2016).

Operation and management

Supporting parallel industries to mining and supporting health and education. The assurance of essential services such as health and education must be a right of the communities surrounding the mining areas as well as users of the rivers and underground waters, and it should be the responsibility of both the companies that are exploiting those natural resources as well as the local government and regulators.

Zarsky and Stanley (2013) performed a comprehensive in situ study of the socioeconomic consequences of gold mining in a case study in Guatemala; the concepts of strong and weak social and environmental responsibility are discussed in depth. Ultimately, the study reported few net benefits of mining for neighboring communities and strongly emphasized the role that the mining industry must play in supporting parallel initiatives to make mining sustainable.

Moreover, it is necessary to consider that after the mines' closure, the mine workers are left with no jobs; even during the operational phase, not everybody can be involved in the mining activity. However, due to the mine, everybody would have to live with the increase in land value and cost of living. In addition, other social problems, such as the absence of investment in the region by the temporal workers, prostitution, and so forth, also arise as significant problems. Therefore, mining companies should support parallel activities and industries in mining to encourage the community to be self-reliant. Brucejack Gold Mine also plans to support self-reliant communities and promote sustainable development (CEAA, 2013). This article recommends that mining companies support farmers who would share the remediation processes of the land as well as parallel industries formed from the beneficiation of the waste mineral and/or phytoremediation business (biorefineries).

Ethical consumption. The consumers' awareness of consumption reduction is a first step that may be considered globally for a world with finite resources. Attention is needed to disrupt consumer perceptions to encourage them to adopt sustainable practices and consumption and also to disrupt corporate images to encourage companies to adopt sustainable practices (European Commission, 2020; UNDP, 2016). The life cycle of the mine products needs to be more visible so that consumers feel responsible.

Such awareness recommendations that result in ethical consumption may comprise mapping mineral origin, fair trade, exposing bad practices, and abolishing planned obsolescence. Multinational companies may have subsidiaries that do not comply with the standards of best-known mining practices, and the multinational is not obliged to review those subsidiaries since they are not legally related (Suppa & Bureš, 2020). Some countries have human rights violations and fund armed conflicts by the mineral exploited (Ullah et al., 2021; UNEP, 2012). It seems necessary to make a mapping of these companies around the world to make it possible to trace the origin of the dirty goods. By exposing bad practices, it may be possible to encourage companies to adopt fair practices. Rwanda's Government and the NGO "Enough" are pushing for this change (Lekakis, 2014).

Planned obsolescence is the way businesses make consumers buy new hardware. This practice should be abandoned since it is contrary to the United Nations' goals of resource efficiency and ethical consumption SDG 12 (UNDP, 2016). Instead of improving durability, allowing repair and repurposing should be promoted, increasing strategies such as swapping, borrowing, and leasing (Pomykała & Tora, 2017). Ultimately, ethical consumption is a political strategy that could shape the industry and make mining more sustainable.

Waste as a resource. For mining to be sustainable, it should support the circular economy package, which gives directives on waste prevention, promotes prolongation of the life cycle by reuse and recycling, and extends producer responsibility for end-of-life products such as electronics, batteries, accumulators, and metals (European Commission, 2020). The European Association of Metals, following the circular economy package, identified five priorities in the mineral sector: product design, chemical management, waste, global trade, and climate 2050 strategy (Eurometaux, 2020). The megatrends in natural resource utilization in Australia have been studied in relation to the extraction and processing of minerals, including ore milling, ore grades, open cut versus underground mining, overburden and/or waste rock, and economic resources (Mudd, 2010). This study reported critical issues such as declining ores' grades, increased waste rock, and associated liabilities. Environmental problems related to the resource intensity for gold and uranium present challenges for energy consumption, water usage, and cyanide use, as well as greenhouse emissions. Detailed data can be found in Mudd (2010). It is necessary to find ways to better utilize mining waste as a resource and develop novel technologies to extract the maximum quantity of metals from it (Kanalli et al., 2015; Shekdar, 2009). Minerals extracted in minor concentrations should be utilized elsewhere, or to develop techniques that allow the maximum extraction of the tailings, reprocessing minerals, using them as aggregate, soil additive, construction mineral, landscaping material, an aggregate component for building materials, mineral processing applications, copper-rich paints, and so forth (Pappu et al., 2007; Rajendran & Gambatese, 2007). Maximum resource utilization could also involve using old mine excavations for seasonal energy storage and pumped hydropower or compressed air storage technologies. Another essential part of waste utilization is using biomass waste as feedstock in a biorefinery (see Biomass valorization).

Replacing toxic minerals and materials. Toxic minerals and materials are a significant problem related to mining activities. Some mining resources have the potential to become sustainable with sound techniques that render toxic effluents useful or innocuous. Benign by design methodology aims to produce green chemicals and materials. The molecular building blocks are critically assessed regarding their toxicity and environmental friendliness to create less toxic or nontoxic chemical substances and materials while attending to the product's effectiveness, acceptability, and biodegradability (Zuin, et al., 2021). However, some minerals and processes do not have this potential, such as mercury utilization, and therefore are being phased out by the Minamata Convention (Lennett & Gutierrez, 2014; UNEP, 2013). Also, the EU has banned halogen bulbs since September 2018. Unfortunately, it is not so with fracking, even when it has severe consequences, including the induction of seismicity close to fracking wells (Meng & Ashby, 2014). Concerns regarding shale gas fracking had been expressed by Olsson et al. (2013) regarding some pollutants found in German facilities such as Cl, Sr, Ca, Ba, S, K, Li, Fe, Mn, Mg, Ni, Pb, Zn, acetate, and formate. The authors recommend recycling the flow backwater. Gordalla et al. (2013) also reported Hg, As, Pb, Zn, Cd, BTX, PAHs, and radioactive elements, with fracking as a toxicological threat to groundwater and drinking water.

Toxic elements and nonenvironmentally friendly practices should be reduced. The REACH regulations in Europe have phased out several toxic materials and continue to work toward making the chemical industry as environmentally friendly as possible. Germany, for instance, closed its last coal mine in 2018 and is determined to become greener by using renewable energy sources (Scholl & Freudenstein, 2018; Schulz & Schwartzkopff, 2015). However, Germany is a significant importer of Colombian coal (Vögele & Govorukha, 2022). Colombia's giant coal mine, El Cerrejon, Guajira, is in production in an arid region with limited water resources and no surplus (Ospina-Noreña et al., 2017). Meanwhile, neighboring communities report starvation and loss of ecosystem services (Contreras et al., 2020). Therefore, in a highly interconnected and globalized world, it is necessary to look at the complete material flow analysis and supply chain to replace minerals and materials globally.

Emergency planning

High-risk impacts due to accidents could occur through physical contact, toxic contamination, and resource scarcity. Some recommendations are as follows:

Mock drills

Currently, disaster preparedness is arranged by mining companies and governments. The contingency plans, the chain of responsibility, and the authority to take action are very well established (UNECE, 2014). In the 2015 disaster in Minas Gerais, there was a lack of functional alarms that alerted the population so that they could take action to evacuate the community (Zago et al., 2019).

It seems necessary and advisable that the population neighboring the mine sites' radius of influence be aware of the possible risk and prepared in case of an emergency. This preparation should involve drills and exercises in which the community would participate, the authorities being the coordinating entity together with the mining companies and NGOs.

Environmental monitoring

The monitoring of the environment is typically carried out by trained personnel who wear protective gear to ensure the safety of the mining operations. However, adjacent communities often reside in the area and can play an essential role in environmental monitoring. These communities are able to detect early warning signs of potential danger, such as changes in the water quality, and help to prevent or mitigate any adverse impacts of mining activities on the environment.

Therefore, it would be necessary to encourage the local population to monitor the river and air. Additionally, people can be provided with measurement kits so that the river quality would be monitored by those interested in its conservation. Also, biological indicator species such as nematodes (Šalamún et al., 2012), earthworms (Protopopov et al., 1999), microbes (Bosecker, 2001), and microarthropods (Lakshmi & Joseph, 2017) could serve to monitor the surrounding areas.

Closure and rehabilitation

Phytoremediation. The pollution caused by mining accidents endangers whole ecosystems and the services they provide because of hazardous materials and destruction capacity. Long-term reclamation and rehabilitation planning using phytomanagement are recommended from the operational phase of a mine. Mirgorodsky et al. (2013) worked on restoring a former uranium mine in East Thuringia, Germany. The soil was left contaminated with hazardous substances and radionuclides. The remediation process was carried out using plant species with different treatments. Successful synergies were reported with mycorrhiza and bacteria (metal-resistant *Streptomyces*) and soil amendment strategies (pH and organic matter adjustment). They also included a step on valorizing the biomass waste from which combustion and biogas production were planned. Smelting sites had also been studied, and biochar amendments from 2% to 5% increased soil pH, electrical conductivity, and water-holding capacity. Higher percentages showed reduced bioavailability and toxicity of Cd, Pb, and Zn by immobilizing them (Lomaglio et al., 2018).

Phytoremediation also helps to restrict the movement of water and contaminants, preventing them from coming into contact with people and the environment in general, avoiding erosion, and incorporating carbon into the soil. For example, poplars take up a large amount of groundwater, absorbing and transferring contaminants to the surface, thus purifying groundwater (Volk & Daley, 2016).

Studies have reported synergism between mycorrhiza varieties and bacteria. The bacteria make nitrogen available, and the mycorrhiza increases the absorption of other elements, such as phosphor (Rivera & Fernández, 2003). Rhizobacteria could also promote photodegradation by releasing phytohormones, helping the absorption of phosphates, and inducing redox reactions (Langella et al., 2014). Bacteria of the genera *Halomonas* and one *Bacillus* localized on the rhizosphere have been found to stimulate plant growth and resistance to salty soil for *Allenrolfea occidentalis* (Kearl et al., 2019).

Carbon sequestration incentives. The “4 per 1000” initiative launched by the French government at COP21 in Paris in December 2015 proposes to recover the soil of the earth by incorporating organic carbon by 4 g/1000 g of CO_2 every year (organic carbon sequestration; Lal, 2016).

Biological agriculture comprises a series of environmentally friendly techniques. These techniques involve reducing pesticide use by incorporating plants that repel pests (allelopathy) and agroforestry (FAO, 2018; Muzell Trezzi et al., 2016). The idea is to stabilize climate in addition to ensuring food security, with good critical practices such as keeping the ground covered, engaged in CO_2-extracting photosynthesis, minimizing tillage, utilizing trees as boundaries, maximizing biodiversity, incorporating perennials, introducing more intermediate crops, row intercropping, grass strips, and rotating crops.

Biomass valorization. To promote the use of phytoremediation, it is essential to ensure the sustainability of biomass production. Mineral extraction (phytomining) may be low efficient and laborintense; however, it is not the only process to be considered. Foremost, the process restarts the land reclamation on the land of low development value to provide ecosystem services that otherwise will not be provided. Additionally, the biomass is to be marketable. Robinson et al. (1997) calculated the viability for a metal concentration of 1% dry mass on a hyperaccumulator with an average annual biomass yield of 30 ton/ha and found that only Co, Ni, Sn, Cd, Mn, and noble metals would be profitable. Nickel biomass yield was of 22 ton dry biomass/ha crop when using *Berkheya coddii, which* was capable of hyperaccumulating 1.8–7.8 g/kg of nickel above ground. The plant could remove 168 kg Ni/ha (Robinson et al., 1997). Recently, Jiang et al. (2015) simulated financial gain with different scenarios; successful combinations were found for biomass with high energy value and high metal accumulating capacity.

After extraction of metals and/or metalloids, the biomass may be feedstock for a biorefinery to produce essential oils or building blocks for biomaterials such as bioplastic, which may pose an excellent alternative to the growing trend of using this biomass as an energy source. Maddhesiya et al. (2022) enhanced the productivity of some perennial aromatic grasses on marginal lands through plant growth-promoting rhizobacteria (PGPR) and reported oil yields of 16.38, 71.14, 53.13 and 49.49 kg/ha, respectively, for *Vetiveria zizanioides* (vetiver), *Cymbopogon citratus* (lemongrass), *Cymbopogon martinii* (palmarosa), and *Cymbopogon winterianus* (citronella). Tailings from mining regions amended with organic matter and rhizobacteria were used to cultivate *Chrysopogon zizanioides* (vetiver), *Cymbopogon citratus*, and *Cymbopogon winterianus*, giving yields of biomass 16, 10, and 4 kg/ha/year, respectively (Zago et al., 2019). Using PGPR, a high net return of 2094.95 dollars for the total crop cultivation of *V. zizanioides* was demonstrated.

Figure 2 shows the predominance diagram of iron at the site of the disaster in Brazil from 2015 tailings. On this chart, the redox potential Eh (V) versus pH decides which chemical species is predominant. Iron is more biologically available in the form of Fe II, which is toxic. The presence of organic matter improves the soil, and iron is transformed into a carbonate that immobilizes the metal. Biorefineries must involve processes to manage toxic waste and add value to biomass. Proper ecotoxicological risk assessment and certification of the bioproducts must be in place so that there is no risk for the bioproducts entering the food chain.

Recent studies showed a high accumulation of toxic metals in native plant *Artemisia vulgaris* tissues grown in polluted soils contaminated with a range of 71.6–3480 mg/kg of copper from an open mine in Armenia (Ghazaryan et al., 2019). The species is a permanent grass; hyperaccumulated copper was 50 mg/kg in shoots and 70 mg/kg in roots, accounting for 3 ton/ha/year of dry mass. These results demonstrate that it is possible to valorize biomass so that the remediation is valid in a sustainable way. Ultimately, phytoremediation, followed by biorefinery processing, would valorize biomass; however, more research is needed in this regard.

 DOI: 10.1002/ieam.4769

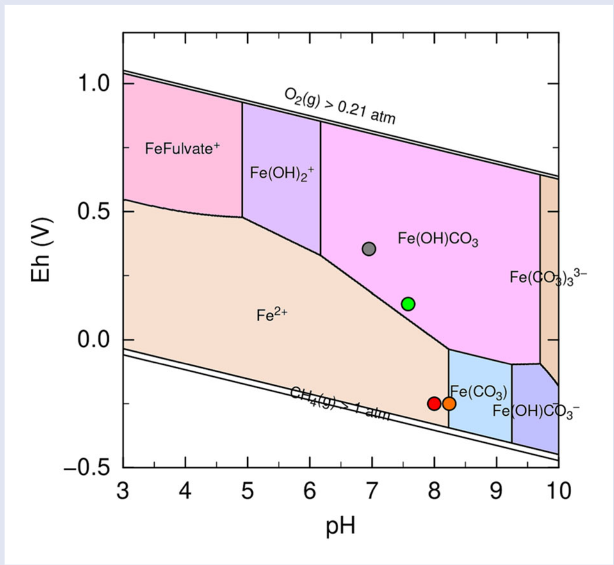

FIGURE 2 Iron predominance diagram in tailings of the Brazil Samarco disaster. Predominance diagram of iron Eh (V) versus pH. Samples from tailings from the Brazil Samarco disaster in 2015. Tailings and compost samples' mineral concentration data were taken from Zago et al. (2019) and Silva et al. (2017). Sample number 1 (red dot: Fe II in the tailings) and sample number 2 (gray dot: Fe in compost) were reported by Zago et al. (2019). Sample 3 (green dot: Fe in mixture 3:2 of the two first samples) and sample 4 (orange dot: Fe in tailings) were reported by Silva et al. (2017). The database used was PRODATA_SIT_Mine_RedoxO2_1.4.dat

Progressive rehabilitation in situ would require that the high metal and/or metalloid content on tailings waste be treated before it is released into the environment as a first step. This means utilizing existing techniques to clean this waste, which involves chemical treatment, physical removal, and biosorption. These treatments may include laying an impermeable liner, building drainage, char (Lomaglio et al., 2018), and bare rocks to increase buffering capacity, water retention, and nutrient capacity and use of tailings with soil and amendments (pH, organic carbon, mycorrhizas, and bacteria) with pioneer species and quick-growing gramineous and legumes and harvesting the resulting crops, extracting the associated metals, and reincorporating fertilizer and finally, the building of a living fence with perennial trees that phytostabilizes the terrain but also, in the case of an accident, serves as a contention barrier, and diluting agent; eventually, when decay occurs, using the biomass as an amendment for the soil.

CONCLUSION

This study encourages the use of sustainable practices throughout the mining life cycle. It critically analyzed the problems generated by mining from different areas of the human sphere: environmental, social, and economic. We proposed interconnected solutions seeking to support ecosystem services necessary for sustainable mineral processing. Furthermore, we demonstrated that sustainable practices are possible. Future work on the sustainability of mining should lead scientists to integrate all aspects and ultimately suggest guidelines that could help governments in each country.

AUTHOR CONTRIBUTION

Beatriz Watts: Conceptualization; formal analysis; investigation; methodology; software; writing—original draft; writing—review and editing. **Valéria C. Palmeira Zago**: Conceptualization; writing—review and editing. **Lakshmi Gopakumar**: Conceptualization; investigation; methodology; writing—review and editing. **Karen Ghazaryan**: Methodology; supervision. **Hasmik Movsesyan**: Conceptualization; data curation; validation.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the advisory members for the project “Assistance in safety improvement of Tailings Management Facilities in Armenia and Georgia” at Ecopeace. The authors would also like to thank Professor Alexander Schall and Professor Bernhard Hohlbein for their inspiring discussions. Additionally, the authors would like to acknowledge the support and contributions of Community and Academic Actions for Sustainable Development NGO, Hamburg, Germany. Their expertise and commitment to sustainable development have been invaluable in the development of this research project. There are no funders to report for this submission. Open Access funding enabled and organized by Projekt DEAL.

DISCLAIMER

The authors declare no conflicts of interest. The authors assume no responsibility or liability for any errors or omissions in the content of this article. The information contained in this article is provided on an “as is” basis with no guarantees of completeness, accuracy, usefulness, or timeliness.

DATA AVAILABILITY STATEMENT

All supporting material for this article can be accessed from figshare: https://doi.org/10.6084/m9.figshare.19401011.v5. The figshare file contains (1) the raw data for the iron predominance diagram in Tailings of Brazil Samarco disaster and (2) Supporting Information: Table S1, which lists incidents related to the European tailings mining facilities considered in this study.

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REFERENCES

Agarwal, S., Satyavada, A., Kaushik, S., & Kumar, R. (2007). Urbanisation, urban poverty and health of the urban poor: Status, challenges and the way forward. *Demography India*, *36*, 121–134.

Bodnaruk, A., O'Brien, W., & Simonov, A. (2016). Captive finance and firm's competitiveness. *Journal of Corporate Finance*, *37*, 210–228. https://doi.org/10.1016/j.jcorpfin.2015.12.018

Bosecker, K. (2001). Microbial leaching in environmental clean-up programmes. *Hydrometallurgy*, *59*(2–3), 245–248. https://doi.org/10.1016/S0304-386X(00)00163-8

Canadian Environmental Assessment Agency (CEAA). (2013). *Brucejack gold mine project: Application for an Environmental Assessment Certificate/Environmental Impact Statement*. https://www.ceaa.gc.ca/050/documents/p80034/99821E.pdf

Carmo, F. F., Kamino, L. H. Y., Junior, R. T., Campos, L. C., Carmo, F. F., Silvino, G., Castro, K. J. S. X., Mauro, M. L., Rodrigues, N. U. A., Miranda, M. P. S., & Pinto, C. E. F. (2017). Fundão tailings dam failures: The environment tragedy of the most significant technological disaster of Brazilian Mining in the global context. *Perspectives in Ecology and Conservation*, *15*(3), 145–151. https://doi.org/10.1016/j.pecon.2017.06.002

Conesa, H. M., Evangelou, M. W., Robinson, B. H., & Schulin, R. (2012). A critical view of the current state of phytotechnologies to remediate soils: Still a promising tool. *The Scientific World Journal*, *2012*, 173829.

Contreras, D., Voets, A., Junghardt, J., Bhamidipati, S., & Contreras, S. (2020). The drivers of child mortality during the 2012–2016 drought in La Guajira, Colombia. *International Journal of Disaster Risk Science*, *11*(1), 87–104. https://doi.org/10.1007/s13753-020-00255-0

Eurometaux (European Association of Metals). (2020). *EU Circular Economy Package: Waste legislation priorities to secure the value of European metals*. https://eurometaux.eu/media/2070/circ-econ-action-plan_eurometaux-detailed-recommendations_final_june-2020.pdf

European Commission. (2020). *EU reaches landmark agreement on conflict minerals regulation*. https://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/regulation-explained/

Food and Agriculture Organization of the United Nations (FAO). (2018). *Sustainable agriculture for biodiversity: Biodiversity for sustainable agriculture* (pp. 48). FAO.

Fröberg, K., & Waris, A. (2011). *Bringing the billions back: How Africa and Europe can end illicit capital flight*. Forum Syd Förlag.

Garbarino, E., Orveillon, G., Saveyn, H. G., Barthe, P., & Eder, P. (2018). *Best available techniques (BAT) reference document for the management of waste from extractive industries*. Publications Office of the European Union.

Ghazaryan, K. A., Movsesyan, H. S., Khachatryan, H. E., Ghazaryan, N. P., Minkina, T. M., Sushkova, S. N., Mandzhieva, S. S., & Rajput, V. D. (2019). Copper phytoextraction and phytostabilisation potential of wild plant species growing in the mine polluted areas of Armenia. *Geochemistry: Exploration, Environment, Analysis*, *19*(2), 155–163. https://doi.org/10.1144/geochem2018-035

Globalwitness. (2018). *The defenders: One year on*. globalwitness.org/guardian

Gordalla, B. C., Ewers, U., & Frimmel, F. H. (2013). Hydraulic fracturing: A toxicological threat for groundwater and drinking-water. *Environmental Earth Sciences*, *70*(8), 3875–3893. https://doi.org/10.1007/s12665-013-2672-9

Hinton, J. B. (2020). Fit for purpose? Clarifying the critical role of profit for sustainability. *Journal of Political Ecology*, *27*(1), 236–262.

Jantzi Research. (2008). *Jantzi research recommends Goldcorp ineligible for SRI portfolios*. Jantzi Research Client Alert.

Jiang, Y., Lei, M., Duan, L., & Longhurst, P. (2015). Integrating phytoremediation with biomass valorisation and critical element recovery: A UK contaminated land perspective. *Biomass and Bioenergy*, *83*, 328–339.

Kanalli, S. A., Naagesh, S., & Ganesh, K. (2015). A review on utilisation of mine waste on black cotton soil. *International Journal of Research in Engineering and Technology*, *4*(7), 499–504.

Kar, D., & Curcio, K. (2011). *Illicit financial flows from developing countries: 2000–2009. Update with a focus on Asia*. The Global Financial Integrity.

Kearl, J., McNary, C., Lowman, J. S., Mei, C., Aanderud, Z. T., Smith, S. T., West, J., Colton, E., Hamson, M., & Nielsen, B. L. (2019). Salt-tolerant halophyte rhizosphere bacteria stimulate growth of alfalfa in salty soil. *Frontiers in Microbiology*, *10*, 1849. https://doi.org/10.3389/fmicb.2019.01849

Lakshmi, G., & Joseph, A. (2017). Soil microarthropods as indicators of soil quality of tropical home gardens in a village in Kerala, India. *Agroforestry Systems*, *91*, 439–450. https://doi.org/10.1007/s10457-016-9941-z

Lal, R. (2016). Beyond COP21: Potential and challenges of the "4 per Thousand" initiative. *Journal of Soil and Water Conservation*, *71*(1), 20–25. https://doi.org/10.2489/jswc.71.1.20A

Langella, F., Grawunder, A., Stark, R., Weist, A., Merten, D., Haferburg, G., Büchel, G., & Kothe, E. (2014). Microbially assisted phytoremediation approaches for two multi-element contaminated sites. *Environmental Science and Pollution Research*, *21*(11), 6845–6858. https://doi.org/10.1007/s11356-013-2165-0

Lekakis, E. J. (2014). ICTs and ethical consumption: The political and market futures of fair trade. *Futures*, *62*, 164–172. https://doi.org/10.1016/j.futures.2014.04.005

Lennett, D., & Gutierrez, R. (2014). *Minamata convention on mercury: Ratification and implementation manual*. Zero Mercury Working Group. Retrieved from https://globalpact.informea.org/sites/default/files/documents/Minamata%20Convention%20on%20Mercury%20%20Ratification%20and%20Implementation%20Manual.pdf

Lomaglio, T., Hattab-Hambli, N., Miard, F., Lebrun, M., Nandillon, R., Trupiano, D., & Morabito, D. (2018). Cd, Pb, and Zn mobility and (bio) availability in contaminated soils from a former smelting site amended with biochar. *Environmental Science and Pollution Research*, *25*(26), 2.

MacInnes, A., Colchester, M., & Whitmore, A. (2017). Free, prior and informed consent: How to rectify the devastating consequences of harmful mining for indigenous peoples'. *Perspectives in Ecology and Conservation*, *15*(3), 152–160.

Maddhesiya, P. K., Singh, K., Kumar, D., & Singh, R. P. (2022). Enhancing productivity of perennial aromatic grasses on marginal lands through plant growth promoting rhizobacteria. *Land Degradation and Development*, *33*(15), 2972–2982. https://doi.org/10.1002/ldr.4244

Meng, Q., & Ashby, S. (2014). Distance: A critical aspect for environmental impact assessment of hydraulic fracking. *The Extractive Industries and Society*, *1*(2), 124–126. https://doi.org/10.1016/j.exis.2014.07.004

Mining. (2019). Brazil dam disaster: What's happened since the tragedy? Mining Technology. https://www.mining-technology.com/features/brazil-dam-disaster-whats-happened-since-the-tragedy/

Mirgorodsky, D., Ollivier, D., Jablonski, L., Merten, D., Willscher, S., Wittig, J., Büchel, G., & Werner, P. (2013). Field scale phytoremediation experiments on a former U mining site and further processing of the plant material. *Advanced Materials Research*, *825*, 516–519. https://doi.org/10.4028/www.scientific.net/AMR.825.516

Mudd, G. M. (2010). The environmental sustainability of mining in Australia: Key megatrends and looming constraints. *Resources Policy*, *35*(2), 98–115.

Muzell Trezzi, M., Vidal, R. A., Balbinot Junior, A. A., von Hertwig Bittencourt, H., & da Silva Souza Filho, A. P. (2016). Allelopathy: Driving mechanisms governing its activity in agriculture. *Journal of Plants Interaction*, *11*(1), 53–60. https://doi.org/10.1080/17429145.2016.1159342

MWEI BREF. (2018). *Best Available Techniques (BAT) reference document for the management of waste from extractive industries, in accordance with Directive 2006/21/EC* (EUR 28963 EN). Publications Office of the European Union. https://doi.org/10.2760/35297

National Geographic. (2019). Brazil's deadly dam disaster may have been preventable. https://www.nationalgeographic.com/environment/article/brazil-brumadinho-mine-tailings-dam-disaster-could-have-been-avoided-say-environmentalists

National Statistical Service of the Republic of Armenia (NSSRA). (2017). *Foreign trade of the Republic of Armenia for 2016: According to the commodity nomenclature of external economic activity at 10-digit level*.

Olsson, O., Weichgrebe, D., & Rosenwinkel, K.-H. (2013). Hydraulic fracturing wastewater in Germany: Composition, treatment, concerns. *Environmental Earth Sciences*, *70*(8), 3895–3906. https://doi.org/10.1007/s12665-013-2535-4

Ospina-Noreña, J. E., Domínguez-Ramírez, C. A., Vega-Rodríguez, E. E., Darghan-Contreras, A. E., & Rodríguez-Molano, L. E. (2017). Analysis of the water balance under regional scenarios of climate change for arid zones of Colombia. *Atmósfera*, *30*(1), 63–76. https://doi.org/10.20937/ATM.2017.30.01.06

Owen, J. R., Kemp, D., & Collins, N. (2020). The social risks of mining: An investor view of human rights and social risks in the mining sector. World

Economic Forum. https://www3.weforum.org/docs/WEF_The_Social_Risks_of_Mining_Report_2020.pdf

Panagos, P., Van Liedekerke, M., Yigini, Y., & Montanarella, L. (2013). Contaminated sites in Europe: Review of the current situation based on data collected through a European network. *Journal of Environmental and Public Health*. https://doi.org/10.1155/2013/158764

Pappu, A., Saxena, M., & Asolekar, S. R. (2007). Solid wastes generation in India and their recycling potential in building materials. *Building and Environment*, *42*(6), 2311–2320. https://doi.org/10.1016/j.buildenv.2006.04.015

Pe'Er, G., Zinngrebe, Y., Moreira, F., Sirami, C., Schindler, S., Müller, R., & Lakner, S. (2019). A greener path for the EU Common Agricultural Policy. *Science*, *365*(6452), 449–451.

Phillips, D. (2018). *Brasil dam disaster: Firm knew of potential impact months in advance*. https://www.theguardian.com/world/2018/feb/28/brazil-dam-collapse-samarco-fundao-mining

Pomykała, R., & Tora, B. (2017). *Circular economy in mineral processing* [E3S Web of Conferences]. EDP Sciences.

Protopopov, N. F., Striganova, B. R., & Manakov, J. A. (1999). Vermitechnology for the remediation of degraded soils in Western Siberia. In M. H. Wong, J. W. C. Wong, & A. J. M. Baker (Eds.), *Remediation and management of degraded lands*. CRC Press.

Rajendran, S., & Gambatese, J. A. (2007). Solid waste generation in asphalt and reinforced concrete roadway life cycles. *Journal of Infrastructure Systems*, *13*(2), 88–96.

Rivera, R., & Fernández, K. (2003). *El Manejo eficiente de la simbiosis micorrízica, una vía hacia la agricultura sostenible. Estudio de caso: El Caribe* (p. 166). Ediciones INCA.

Robinson, B. H., Brooks, R. R., Howes, A. W., Kirkman, J. H., & Gregg, P. E. H. (1997). The potential of the high biomass nickel hyperaccumulator *Berkheya coddii* for phytoremediation and phytomining. *Journal of Geochemical Exploration*, *60*, 115–126.

Ruiz Leotaud, V. (2018). *First Nation and British Columbia to share gold mine tax revenue*. http://www.mining.com/first-nation-british-columbia-share-gold-mine-tax-revenue/

Šalamún, P., čRenčo, M., Kucanová, E., Brázová, T., Papajová, I., Miklisová, D., & Hanzelová, V. (2012). Nematodes as bioindicators of soil degradation due to heavy metals. *Ecotoxicology*, *21*(8), 2319–2330. https://doi.org/10.1007/s10646-012-0988-y

Scannell, Y. (2012). The regulation of mining and mining waste in the European Union. *Washington and Lee Journal of Energy, Climate, and the Environment*, *3*(2), 177–267.

Scholl, E., & Freudenstein, P. (2018). *Amid government turmoil, Germany dives into efforts to phase out coal*. https://www.atlanticcouncil.org/commentary/energysource-explains-amid-government-turmoil-germany-dives-into-effort-to-phase-out-coal/

Schulz, S., & Schwartzkopff, J. (2015). *G7 coal phase out: Germany. A review for Oxfam* (pp. 23). Oxfam Deutschland.

Shekdar, A. V. (2009). Sustainable solid waste management: An integrated approach for Asian countries. *Waste Management*, *29*(4), 1438–1448. https://doi.org/10.1016/j.wasman.2008.08.025

Silva, A. C., Cavalcante, L. C., Fabris, J. D., Júnior, R. F., Uidemar, Barral, M. T., Farnezi, M. M., Viana, A., Ardisson, J. D., Eugenio, L., Fernandez-Outon, Lara, L. R., Stumpf, H. O., Barbosa, J. B., Da, L. C., & Silva. (2017). Chemical, mineralogical and physical characteristics of a material accumulated on the river margin from mud flowing from the collapse of the iron ore tailings dam in Bento Rodrigues, Minas Gerais, Brazil.

Suppa, A., & Bureš, P. (2020). Can multinational corporations be responsible for human rights violation of its outsourcee company? Response of national or international law? *International & Comparative Law Review/ Mezinárodní a Srovnávací Právní Revue*, *20*(1), 153–179.

de Souza, I. B. S., de Oliveira, L. L. F., Thomé, R. G., dos Santos, H. B., de Paiva, M. C., & Chequer, F. M. D. (2021). Hydric pollution and its genotoxic potential: An analysis of the Doce river basin after the Fundão dam failure. *Research, Society and Development*, *10*(7), e17010716374. https://doi.org/10.33448/rsd-v10i7.16374

Stanley, G., Jordán, G., Hámor, T., & Sponar, M. (2011). *Guidance document for a risk-based pre-selection protocol for the inventory of closed waste facilities as required by Article 20 of Directive 2006/21/EC*.

Tailings info. (2018). *Tailings storage guidelines and standards*. http://www.tailings.info/knowledge/guidelines.htm

Tomiyama, S., & Igarashi, T. (2022). The potential threat of mine drainage to groundwater resources. *Current Opinion in Environmental Science & Health*, *27*, 100347.

Ullah, R., Khan, M. A., & Akhtar, P. (2021). Multinational corporations and human right violations in emerging economies. *Journal of Business Ethics*, *170*(3), 489–512.

United Nations Development Programme (UNDP). (2016). *Sustainable Development Goals*. http://www.undp.org/content/undp/en/home/sustainable-development-goals.html

United Nations Economic Commission for Europe (UNECE). (2014). *Safety guidelines and good practices for tailings management facilities*. United Nations, New York and Geneva. https://www.unece.org/fileadmin/DAM/env/documents/2014/TEIA/Publications/1326665_ECE_TMF_Publication.pdf

United Nations Environment Programme (UNEP). (2012). Analysis of formalization approaches in the artisanal and small-scale gold mining sector based on experiences in Ecuador, Mongolia, Peru, Tanzania and Uganda: Tanzania Case Study. https://wedocs.unep.org/20.500.11822/31275

United Nations Environment Programme (UNEP). (2013). *Minamata Convention on Mercury*. https://www.unep.org/resources/report/minamata-convention-mercury

United Nations Office for Disaster Risk Reduction (UNDRR). (2022). *PreventionWeb knowledge base*. www.preventionweb.net/knowledge-base/type-content/policy-plans

Vélez-Torres, I., & Ruiz-Torres, G. (2015). Extractivismo neoliberal minero y conflictos socio-ambientales en Perú y Colombia. *Ambiente y Sostenibilidad*, *5*, 3–15.

Vijgen, J., & Nikolaieva, I. (2016). *Improving the safety of industrial tailings management facilities based on the example of Ukrainian facilities* (Project No. (FKZ) 26206, Report No. (UBA-FB) 002317/ENG).

Volk, T. A., & Daley, D. J. (2016). *Sustainable reuse demonstration project using short rotation woody crops for water budget*. Honeywell Inc.

Vögele, S., & Govorukha, K. (2022). Impact of Germany's phase out of coal power plants on developing countries, *Climate and development* (pp. 465–499).

Winkelmann-Oei, G., Rudakov, D., Shmatkov, G., & Nikolaieva, I. (2015). A method for evaluation of tailings hazard. In G. Pivnyak, V. Bondarenko, & I. Kovalevska (Eds.), *Theoretical and practical solutions of mineral resources mining* (p. 600). CRC Press. https://doi.org/10.1201/b19901

Zago, V. C. P., das Dores, N. C., & Watts, B. A. (2019). Strategy for phytomanagement in an area affected by iron ore dam rupture: A study case in Minas Gerais State, Brazil. *Environmental Pollution*, *249*, 1029–1037. https://doi.org/10.1016/j.envpol.2019.03.060

Zarsky, L., & Stanley, L. (2013). Can extractive industries promote sustainable development? A net benefits framework and a case study of the Marlin Mine in Guatemala. *Journal of Environment & Development*, *22*(2), 131–154.

Zuin, V. G., Eilks, I., Elschami, M., & Kümmerer, K. (2021). Education in green chemistry and in sustainable chemistry: Perspectives towards sustainability. *Green Chemistry*, *23*(4), 1594–1608.

