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Review article

A review of the environmental and health implications of recycling mine tailings for construction purposes in artisanal and small-scale mining communities

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ABSTRACT

Technical advancements in mine tailings recycling have led to the production of construction products such as bricks, cement, road pavers, and mortars in artisanal and small-scale mining (ASM) communities. Although such efforts show promise, the environmental, health, and social implications of such practices are often overlooked by stakeholders including researchers, miners, and community members. This paper summarizes and evaluates the environmental and health implications of mine tailings recycling activities (MTRAs) in ASM. A comprehensive review was conducted using both academic and gray literature to analyze the current state of practice linked with environmental and health considerations. From the fifty-three analyzed MTRAs, twenty-three articles considered aspects of environmental concerns, and three studied aspects of health in mine tailings recycling processes. When included, environmental and health considerations mainly focused on toxicity leaching protocols or analyzing health risks and exposure routes of facilities constructed out of mine tailings construction materials. Results suggest that studies mostly focus on lab-scale experiments evaluating the material properties of the MTRAs products and have limited consideration of field application and social concerns. No study considered environmental, health and social implications in unison. To comprehensively address these concerns, a Comprehensive Approach to Recycling Tailings (CART) framework is proposed that can assist communities and researchers to better understand the possible environmental and health implications of MTRAs and to incorporate such understanding into practice.

Abbreviations

MTRAS	Mine tailings recycling activities;
CART	Comprehensive approach to recycling tailings;
MTR	Mine tailings recycling

1. Introduction

Artisanal and small-scale mining (ASM) is a simplified form of ore extraction carried out as an informal sector with little to no mechanization (Hilson et al., 2021; Pedersen et al., 2021), employing more than 45 million people worldwide (World Bank, 2020). At ASM operations, mine tailings, defined as the finely ground residue from the metallurgical processing of ore, are typically disposed of in the most convenient manner possible, oftentimes adjacent to populated areas, piled next to or within nearby surface waters, or dumped in the original mine pit, resulting in long-term sources of pollution. Such lack of management poses a great risk to ecosystems and human receptors through the long-term release of toxic metals and metalloids including cadmium (Cd), lead (Pb), arsenic (As), and selenium (Se) (Johnson and Hallberg, 2005). In gold production, mercury (Hg), and cyanide further complicate tailings management. Awareness of the health implications

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associated with the release of heavy metals by ASM operations is gaining attention in many communities in developing countries, spurring local level action among miners and communities towards formalization efforts (Veiga and Marshall, 2019). As part of such efforts, ASM operations have identified the critical need to initiate sustainable mine tailings management strategies (Veiga and Hinton, 2002).

However, these strategies are the result of years of lessons learned from large-scale mining (LSM). Events such as the Mount Polley mine tailings pond breach in Canada in 2014 (Byrne et al., 2015) and Brumadinho dam collapse in Brazil in 2019 (Silva Rotta et al., 2020), have turned mine tailings and mine waste management into hot topics for governments, communities, and environmental agencies. The past attitude towards waste management in LSM has been illustrated by the industry's propensity for caring more about mitigation than prevention (Owen and Kemp, 2019), something that, until now, had been overlooked by regulators, scholars, and academics. Standards such as the Global Tailings Review (2020) provide global rubrics to help assess and manage the practices that cause concern created around the mining industry and its waste management policies. However, these rubrics are created with a LSM bias, meaning that efforts to translate this to the artisanal and small-scale are limited, albeit important for addressing tailings management comprehensively.

Mine tailings recycling efforts have therefore started to gain traction within ASM, non-governmental organizations (NGOs), governmental organization, academics, and research institutions as a method for mine tailing's management. As described by Schwartz et al. (2021), community-initiated or individual-initiated projects that focus on environmental improvements, or *"positive deviances"* show promise in providing sustainable strategies with long lasting results, rather than technical solutions enforced on a community by external technical efforts. Therefore, focus on the promotion and assistance in such efforts is warranted.

One such mine tailings management strategy gaining popularity worldwide in ASM is mine tailings recycling (MTR), or the conversion of tailings into valuable products, assets, or applications through a reprocessing method that may decrease the exposure of humans and ecosystems to contaminated material (Lottermoser, 2011). Recent efforts in ASM operations and government, research laboratory, and academic studies focus on developing construction products such as cinder blocks, concrete, mortars, adobe bricks, cement bricks, cement blocks, and any variation of the aforementioned materials. Despite the understanding of the applicability and need for such efforts (Schwartz et al., 2021), attempts towards recycling mine tailings are hampered by a lack of technical knowledge regarding the fabrication and production of the construction materials within ASM organizations. Although much literature is available on the technical feasibility of MTR (Aznar-Sánchez et al., 2018; Mohajerani et al., 2019), there is a disconnect between this literature and community implementation (McEwen et al., 2016). Technical improvements are mainly performed in research laboratories with little to no focus on the translations of such knowledge to communities (Ahmari and Zhang, 2012; Chen et al., 2012; Jaarsveld et al., 2000). This disconnect between technical research, community construction, and application create a gap due to the lack of focus on the social and economic factors limiting widespread use and production of feasible and long-lasting alternatives (Lucena et al., 2011). Additionally, efforts focusing on the environmental and health considerations of recycling mine tailings into construction materials exclude technical implications in their studies, furthering the disconnect between the technical, environmental, health, and social implications of MTR (Barbieri et al., 2014; McEwen et al., 2016).

Assessment of the environmental and health implications of MTR is needed to properly understand the risk associated with MTR usage. For example, if a certain type of mine tailings containing a certain type(s) of heavy metals are recycled into cinder blocks, an assessment is needed to understand any exposure issues associated with the usage of the cinder blocks in different applications (e.g., a school, home, retaining wall, etc.). One method of evaluating heavy metal release rate and exposure to these construction materials is through a risk assessment process (Buch et al., 2021; Kan et al., 2021). Typically, environmental and health risk assessments consist of four main steps: hazard identification or data collection, exposure assessment, toxicity assessment, and risk characterization (U.S. EPA, 1989). Hazard identification is defined as the analysis of the source and typically consists of the understanding of the chemicals at a site and their characteristics. For example, in MTR, the initial concentrations of heavy metals in mine tailings, location, and physical properties would be identified. Next, exposure assessment addresses the transport of chemicals and intake levels. This is illustrated by Tirima et al. (2016), in which the environmental remediation project carried out in Nigeria identified bricks with high levels of lead concentration. Toxicity assessment determines toxicity indexes by dividing the effects into carcinogenic and noncarcinogenic, calculating slope factors and reference doses (RfD), respectively. Finally, risk characterization helps quantify risk in a numerical scale, summarizing results and giving useful information to stakeholders for decision making processes.

Without knowledge of the source and pathways of contaminants from recycled mine tailings, it may not be possible to provide communities with an understanding of the risk associated with mine tailings recycling activities (MTRAs). Therefore, our goal is to outline the current state of understanding of the environmental, and health implications of MTRAs, providing a path forward for follow-on efforts to better define the potential adverse effects of human and environmental exposures to MTRAs. This review excludes technical studies that address the scientific fabrication (i.e., production) methods for recycling mine tailings. The reader can refer to recent reviews of MTRAs technology for more information on the fabrication of MTRAs (Aznar-Sánchez et al., 2018; Komnitsas and Zaharaki, 2007; Mabroum et al., 2020; Park et al., 2019; Saedi et al., 2020; Xu et al., 2019). We start by reviewing studies about mine tailings recycling products and analyzing peer-reviewed papers and gray literature in both developed and developing countries to determine the extent that these studies accounted for environmental and health considerations in their efforts. Although the focus of this review was directed to environmental and health implications, some consideration was also placed on the social aspects of community risk perception. Later, we discuss potential environmental and health impacts of MTRAs based on the risk assessment process outlined by the Environmental Protection Agency (EPA) and the National Academy of Science (NAS) (National Academies of Sciences, Engineering, 2009; U.S. EPA, 1989), as well as limited discussion on the social implications, discussing from a comprehensive approach some of the variables that should be accounted for in mine tailings recycling processes. In particular, this paper focuses primarily on the first two steps of risk assessment - hazard identification, and exposure assessment, to better understand the fate and transport of contaminants as well as potential levels of intake. We conclude with suggestions on a path forward that integrates the implications of mine tailings recycling for communities, NGOs, governmental organizations, and researchers to better assess potential environmental and health effects, while at the same time incorporate social concerns when developing MTRAs.

2. Methodology

MTRAs are often conducted in developing countries by ASM operators and sometimes in collaboration with local researchers, NGOs, or universities. Information is typically reported in the form of unpublished reports or project websites and little to no information is available in the form of peer-reviewed literature. This review, therefore combines both peer-reviewed and gray literature in the form of unpublished reports, websites, videos, news, and interviews by the authors with members of communities working with these projects. For an MTRA to be included in this study, a formal document, such as a project report, article, working paper, or web page must be available. Research efforts on the technical aspects (i.e., fabrication methods, new technical advances in production of construction materials) of recycling mine tailings into construction materials are available in the form of peer-reviewed literature but are mostly limited to laboratory testing of fabrication and therefore excluded from this review. Fig. 1 illustrates the subdivision of the case studies in their specific area of focus, including technical (method refinement), environmental (contaminant leaching to the environment), health (exposure risk), and social considerations. This work specifically focuses on the *field studies and applied projects*, where the disclosure of specific locations, mine sites, or communities was detailed rather than the purely technical lab-based studies.

As this review targets the environmental and health implications of MTRAs, we considered two main criteria for identifying studies stemming from the field and applied projects. First, field studies and applied projects address MTRAs from an environmental, health, social, and/or technical fabrication approach (i.e., method refinement), by developing construction materials with the intended purpose of serving community applications. This includes developing tests that assess the environmental concerns, physical properties of the intended materials, or health risks associated with the use of these materials. For example, the subcategory "*Contaminant Leaching to the Environment"* included studies that determine toxic leachability from MTRAs. A study was included in this subcategory if it identified possible environmental concerns caused by these construction materials in the location of their intended use. Similarly, a study was included under the "*Exposure Risk to Public Health"* subcategory if a study recognized the potential exposure pathways a contaminant may have through the construction materials as determined by a health risk assessment, risk characterization, or the acknowledgment that health risks needed to be further assessed. The "*Social Involvement"* subcategory includes studies that discuss any stakeholder engagement or economic considerations. Merely technical and scientific studies fall into the category of "*Method Refinement"* and were only included and analyzed if they considered any of the other categories (health, environment, or social) mentioned above. In addition to the literature focused on MTRAs deployment with the ASM sector, select literature on LSM that meets the selection criteria were also included in this study. Although this work focuses on ASM, best practices from LSM can potentially be applied to ASM MTRAs efforts.

For the development of the methodology, keywords were subdivided into five main categories: object, method, end-use, end-product, and provider. Keywords included "mine tailings", "mine waste", "tailings", "recycling", "reuse", "repurpose", "construction", "ASM", "LSM". Four search engines, Google Scholar, ISI Web of Science, Engineering Village™, and Science Direct were used for the literature review. Given the informal nature of the research and the dearth of information on this topic, data gathered from the search engines were often redundant and required extra steps of refinement for duplicated articles. During this literature review, previously mentioned keywords were used in different combinations to identify the most suitable articles under the pre-established methodology. If a researcher was found to appear multiple times within the keyword search, the profile of the researcher was then examined for additional relevant publications.

Initially, a search was performed using the three first categories of keywords in the Engineering Village, ScienceDirect, Web of Science, and Google Scholar, using the parameters [TITLE-ABS-KEY ((("mine tailings" OR "mine waste" OR "tailings") and ("recycling" OR "reuse" OR "repurpose") and ("construction materials"))]. The time scale of the sample was established between 1960 and 2021. In total, we found 600 results (198, 32, 86, and 284 results, respectively). After refining the search and analyzing redundancy and reading all abstracts from this first search, 551 studies were excluded from the analysis, including conference proceedings, journal articles, books, dissertations, among others.

On a second query using the first, second, and fourth keyword categories [TITLE-ABS-KEY ((("mine tailings" OR "mine waste" OR "tailings") and ("recycling" OR "reuse" OR "repurpose") and (bricks" OR "cement" OR "concrete" OR "mortars" OR "plasters"))], fifty-seven more articles were selected. This selection was based on previously mentioned search engines, as well as Google searches, news, and other webpages where databases indexing do not reach. From this search, twenty-four articles were considered suitable for the current study. After reviewing and comparing articles from both queries, and analyzing their suitability for the pre-established criterion, twenty articles from the first query and all the twenty-four articles from the second query were selected for the present study. In total, forty-four articles from published literature were analyzed in our review using environmental, health, and social considerations in their analysis.

Projects using mine tailings in construction materials have been directed by communities, non-governmental organizations (NGOs), mining companies, or other entities without the resources to publish in peer-reviewed journals, illustrating another body of literature to be included in our study. As shown by literature reviews on other topics in environmental management (O'Brien et al., 2020), community-driven projects are often unpublished or published as gray literature. For this work, the so-called gray literature is considered upon the basis of visible and verifiable information. For the gray literature, several web pages were used to find news, interviews, or related governmental information about mine tailings recycling strategies around the world. From Open gray and WorldCat, the search strings used were [TITLE-ABS-KEY "tailings discipline:(08 L - Mining)" and "kw:mine tailings AND kw: recycling"], respectively, obtaining three more articles. Google searches in both Spanish and English resulted in three more news articles on recycling strategies in Latin America. Interviews carried out by the authors in communities were also considered part of gray literature accounting for three more studies. In total 53 studies were considered for our literature review considering both gray literature as well as published literature. For the purpose of this paper the studies, articles, interviews, and other types of literature used for the review are called *"Mine Tailings Recycling Activities"*.

3. Results

In our literature review, we discovered different types of mine tailings recycling methods and end products that present different potential

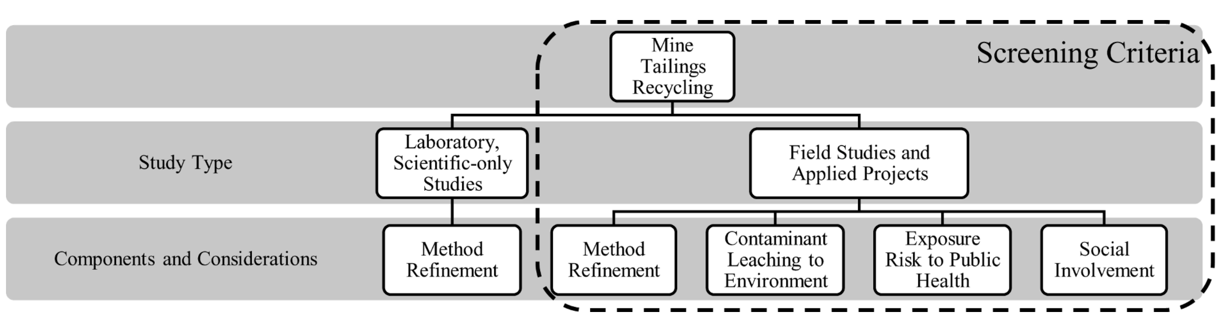

Fig. 1. Screening criteria (dotted box) used to select mine tailings recycling activities. The literature review was based on study type (lab or field), environmental, and health considerations.

risks and opportunities in terms of environmental concerns and health impact. First, we briefly discuss the commonly used construction material processing methods (e.g., Portland cement, geopolymerization), the end products, and final usages of the construction materials that we identified through our literature review. This is then followed by a review of what has been previously considered from an environmental and health perspective. Finally, we analyzed these results using as guide source and pathway analysis by Watts (1998).

3.1. MTRAs processing and fabrication methods

The development of products such as bricks, mortars, or grout from mine tailings recycling involves different processing methods that vary widely in the literature from simple concrete mixes to innovative geopolymerization techniques. From the literature review, we identified two main recycling processing methods carried out for the development of construction materials: the mixture of Ordinary Portland Cement (OPC) with mine tailings for the production of concrete-based materials (twenty-eight MTRAs) and alkaline activation, specifically geopolymerization (ten MTRAs). Four MTRAs did not specify fabrication methods but rather focused on the material properties of the final products created from mine tailings. Additionally, ten MTRAs did not study a specific method of fabrication or material properties of the end product but rather focused on the consideration of environmental topics, such as the analysis developed to understand the behavior of the contaminants in the environment, or the application of mine tailings recycling projects in communities. Finally, one MTRA used heated pellets.

The choice of the production method should be dependent upon the contents within the tailings themselves (e.g., silica and alumina) and the context in which the materials are being produced. Table 1 summarizes the main recycling processing methods of the construction materials and their respective chemical element associated with the mine tailings ore composition. Although we could not find a direct relationship between the ores and the selection of a specific method as shown in Table 1, presumably the selection of method is directly influenced by the availability of resources specific to the location, such as the availability to buy mixers, compression machines, or even cement for the OPC mixture, and precursors/activators in the alkaline activation method.

There are other technical approaches in the activation of mine tailings, mechano-chemical activation (Fernández-Bertran, 1999; Sobolev, 2005), and hydrothermal processes (McDonald et al., 2016). These activation processes are used to facilitate the alkaline processes of recycling mine tailings, helping change the chemical structure at a molecular level of the tailings for the preparation of different experiments. These methods were not considered for this study since none of the analyzed MTRAs that incorporated environmental, health, and social aspects into their project used these specific processing methods. However, these are other possible technical avenues that may be available for future research on the topic.

3.2. Fabricated products and final application

For this work, we investigated both the final products from the MTRAs and the final application of the product. Fabricated products are defined as the physical object, resulting from the fabrication methods, such as bricks, road pavers, concrete, and their variations. The final application, instead, is defined as the usage of these products for different purposes such as community, industrial usage, or commercial purposes. As seen in Table 2, the main fabricated products in the studies were concrete and mortars with twenty-seven MTRAs and bricks with ten MTRAs. Likewise, nine MTRAs described the use of road pavers and road base materials for road transportation purposes.

Brick production mainly included two categories, soil-based bricks, and cinder blocks, and this final product was the most commonly observed when applied in ASM communities. Soil-based bricks use tailings, cement, and soil to create adobe-like bricks for community purposes as documented by The Environmental Health Council (2015) as part of a remedial investigation in Huancavelica, Peru. In contrast, cinder blocks generally use geopolymers or a mixture of OPC to produce a concrete masonry unit. For example, in Mindanao, Philippines, and Karnataka, India, the use of geopolymerization (Aseniero et al., 2019) and mix with OPC (Roy et al., 2007) with gold tailings has been documented in the production of bricks. Other examples of brick production can be found among ASM communities. The National Education Service of Colombia explored the opportunity of using the mixture of OPC as well as geopolymers to recycle mine tailings and degraded soils from artisanal and small-scale mining (ASGM) communities into bricks for community utilization (SENA, 2020). Similarly, ASM miners in Chile have been developing bricks out of mine tailings since 2016 (Radio Maray, 2019). Finally, in Peru, an undergraduate thesis analyzed the fabrication of bricks based on mine tailings for masonry purposes (Cárdenas Ticlavilca, 2019). In general, little to no details were provided that specifically outlines where these bricks are used long-term or the final application they may have. Thus, there is a clear gap between the processing, application, and end-use considerations.

3.3. Environmental and health consideration in MRTA literature

In total, 38 MRTAs acknowledged some aspects of the environment or health. This section will summarize these findings based on the acknowledgment of two broad categories of risk assessment - Source Analysis (Hazard Identification) and Pathway Analysis (Exposure Assessment) (Watts, 1998). Although not the main focus, social implications will be discussed under a risk perception approach and community engagement perspective (Boholm, 2003).

3.3.1. Source analysis

The analysis of the MTRAs in relation to environmental implications was mostly directed towards the identification of the leachability of heavy metals from the recycled construction materials to determine the mobility of heavy metals. Using this approach, 23 MTRAs used various leaching procedures, such as the Toxicity Characteristic Leaching Procedure (TCLP) (Lu et al., 2019), Synthetic Precipitation Leaching Procedure (SPLP) (Taha et al., 2019), and/or weathering cell tests (Argane et al., 2016) (Table 3). From the 23 MTRAs, 13 of these were in a developing country such as Malaysia, Morocco, Peru, Colombia, and Indonesia.

The most common test used among the studies to determine the potential of heavy metal release was the EPA Method 1311, TCLP. Although this test and others were not specifically designed to test mine tailings-based products (e.g., TCLP, SPLP), results can be used to provide

Table 1
Main recycling processing method of the construction materials and their respective chemical element associated with the mine tailings ore composition.

Processing method	Associated elements to tailings ore	No. of studies
Alkali-activation (Geopolymerization)	Al, Fe, Co, Au	10
Mixture with OPC	Fe, W, Pb, Au, Co	28
Heated Pellets	Au, Al	1
Not Specified	Pb, Zn, Au	4
Not Studied	Au, Hg, Pb, Zn	10

Table 2
Material produced, and fabrication methods used for the analyzed MTRAs.

Fabricated products	Fabrication methods	No. of studies
Concrete and mortars	Mix with OPC, Geopolymerization	27
Bricks (cinder, soil)	Mix with OPC, Geopolymerization	10
Road pavers	Mix with OPC, Geopolymerization	9
Not specified	–	7

Table 3
Summary of the contaminant mobility tests performed in the MRTA literature.

Entity	Method	Name of the standard test	No. of studies*
EPA	Method 1311	Toxicity Characteristic Leaching Procedure (TCLP)	10
EPA	Method 1312	Synthetic Precipitation Leaching Procedure (SPLP)	6
ABNT	NBR	10,004, 10,005, 10,006, 10,007	4
ASTM	D5744-18	Laboratory weathering of solid materials using a humidity cell	2
–	–	Other tests performed	8

*Some MTRAs used more than one test.

some indication of the behavior of the mine tailings recycling products under specific scenarios (i.e., acidic conditions). Leaching tests used for the MTRAs addressed heavy metal contamination, quantifying the concentration in the leachates of metals and metalloids such as: As, Zn, Pb, Cu, Cr, Cd, Fe, Ni. The targeted metals analyzed varied based on the authors' knowledge of the site and metals that each mine site produces. Leachate analysis was predominantly tested at two different stages in the mine tailings recycling process: (1) analysis of the mine tailings before any treatment or fabrication and (2) analysis of mine tailings' final products (i.e., construction materials). Studies that investigated the chemical contents of mine tailings prior to any treatment illustrated how most mine tailings had metals and metalloid concentrations above established limits. In contrast, results from leachate studies for final MTR products suggested that there was a reduction of contaminant mobility below detection limits (Argane et al., 2016; Argane et al., 2015; Kiventerä et al., 2018; Mahmood and Elektorowicz, 2020). In some cases, this reduction of heavy metal concentration was due to the contents of abundant neutralizing minerals, and the crystalline structure formed in the fabrication process of these construction materials, thereby encapsulating the hazardous metals within the structure of the final product (Argane et al., 2016, 2016). However, we could not find any MTRAs that have developed a uniform statistical sensitivity analysis that verify the reduction in mobility of contaminants.

Since environmental considerations were taken into account by previous literature to be a secondary objective to the fabrication process for the production of MTRAs, triplication of samples, comparison of results, or quality assurance were not disclosed in these studies. For example, one MTRA analyzed the mobility of contaminants using a "chemical and geochemical characterization" approach, where tailings samples were exposed to meteoric water (i.e., distilled water with HCl). According to the authors, this was to simulate exposure to Brazilian rainfall to determine the concentration of metals in the leachates. Although results show low concentrations of heavy metals, authors recommended a more complex study to determine the chemical speciation of metals in mine tailings, since this study did not utilize a standardized test (dos Santos et al., 2019).

In addition to the environmental assessments presented above which primarily focused on the mobility of contaminants within the final products, one MTRA performed a more comprehensive approach to the environmental impacts by evaluating the environmental benefits of utilizing treated copper tailings for concrete mixes through a life cycle assessment. Using environmental indicators such as terrestrial acidification, fine particulate matter formation, freshwater ecotoxicity, and water consumption. The authors demonstrated that the performance of each environmental indicator is dependent on the characteristics of the tailings. However, a better fabrication method that increases mechanical performance is less likely to negatively impact the environmental performance of these indicators (Vargas et al., 2020).

For the environmental impact analysis, multiple barriers were identified in this literature review. Certain considerations should be taken into account, as mentioned by Argane et al. (2016); "…These conclusions [immobilization of contaminants] would not be reached by simply examining bulk metal concentrations or using tests such as TCLP and thus underlines the importance of combining chemical, mineralogical, and geochemical characterization approaches and various leaching tests for assessing the reuse potential of mine tailings". Furthermore, the study by Perry et al. (2005) advises the incorporation of other environmental aspects to produce a more generalized understanding of mine tailings recycling, suggesting further evaluation of potential dust contribution for additional heavy metal contamination exposure. Expanding upon this idea, frameworks like the one proposed by Petkovic et al. (2004), in which the analysis of recycled materials in road construction is considered combining European standards for the characterization of waste and Norwegian guidelines for road construction, provide an additional analysis tool that includes the determination of site-specific parameters influencing leaching behavior, long term leaching scenarios, and behavioral mathematical models of natural leaching processes, guiding the decision-making process from an overall perspective of the environmental effects.

3.3.2. Pathway analysis

During an exposure assessment, the transport of a chemical from the environment to an individual and the levels of intake by the individual are studied. From the review carried out, only three MTRAs discussed the health risks associated with exposure and toxicity assessments. Although the health approach for these studies did not necessarily follow regular risk assessment steps, such as hazard identification, exposure assessment, toxicity assessment, and risk characterization, they often acknowledged the relevance of incorporating health risk-based studies when analyzing the recycling of mine tailings, hence their incorporation in this review. From these three MTRAs, the pathways considered were water (W. J. Ju et al., 2018), soils (Perry et al., 2005), and air (Hagan et al., 2015). The main exposure routes examined in these studies were inhalation, ingestion, and, in cases in which the recycled material needed to be manually manipulated, dermal contact.

Only the study conducted by W. J. Ju et al. (2018) developed a combined approach to analyze the environmental concerns from both hazard identification and exposure assessment standpoint, where leaching test results and major exposure routes were combined to promote safer recycling of mine waste. In this specific study, two different analyses were conducted under a two-stage assessment method. First, hazard identification was carried using SPLP tests and Korean Standard Tests for Solid Wastes to determine the contaminants present in the tailings and their leachability properties. Then an exposure assessment was developed that considered the ingestion of soils, particulate matter in the air, and contamination in water as primary exposure pathways. This was later combined with a risk assessment to determine ingestion, inhalation, and dermal contact rates, as well as the carcinogenic and non-carcinogenic risks. This MTRA focused on two main populations: industrial workers involved with the fabrication of construction materials and community members who are in direct contact with the recycled mine tailings. Results show that both non-carcinogenic and carcinogenic risks are mitigated due to the fabrication method, but dermal contact can pose a higher risk in industrial areas where manipulation of contaminated materials was more frequent.

Other studies that have also addressed health risk assessment from a similar approach, include those conducted by Hagan et al. (2013) and McEwen et al. (2016) which analyzed Hg contamination and health risk associated with adobe bricks in Peru and Bolivia in ASM communities. In these analyses, special focus was given to dust and possible inhalation issues related to indoor air quality, given the Hg volatilization and dust release rates. Results show a high concentration of heavy metals in bricks posing potential health risks to people through ingestion and inhalation of adobe brick particles.

3.3.3. Additional social considerations

Although not the main focus of this study the literature was reviewed to understand how often social considerations such as community engagement, perception of risk, or cost-benefit analyses were included in the studies. Community involvement is crucial for the successful implementation of projects. By engaging communities early-on in the project (O'Brien et al., 2019) and incorporating local knowledge into project definition and design (Ongley and Booty, 1999), projects are more likely to garner community buy-in and become more sustainable. For applications of MTRAs in ASM communities, it is vital to find a way to meaningfully engage with the community, though examples of this are limited in the literature.

As stated by Aznar-Sánchez et al. (2018) in their review of worldwide advances in mining waste management, there is a lack of analysis on the sustainability of mine waste repurposing. Aznar-Sánchez et al. (2018) proposed that the future of mine tailings repurposing should focus on studies related to social welfare and suggests multidisciplinary approaches that involve technical and socioeconomic methods that ultimately give meaningful information to the stakeholders for decision-making processes. However, our literature review identified a lack of consideration for communities in recycling mine tailings and application of final materials within a community, as zero MTRAs directly considered community engagement or stakeholder involvement at any level. Instead, MTRAs literature focused on the economic implications of the projects, considering that as playing a role in social buy-in. For example, several authors analyzed mine tailings through an economic frame by examining mine tailings repurposing as a circular economy, which is an economic system that takes advantage of waste and enduring use of resources (Beltrán-Rodríguez et al., 2018; Ricardo et al., 2019). Additionally, eight MTRAs considered, to some extent, a cost-benefit analysis as a metric for determining community interest in the project. These cost-benefit analyses varied in scope and reach. For example, some articles discussed the unit price of fabricated bricks under specific studied conditions (Cárdenas Ticlavilca, 2019; Roy et al., 2007), whereas others considered a more administrative approach to determine the percentage of mine tailings required for an optimum concrete cost reduction, and savings pertaining the use of copper mine tailings (Muleya et al., 2020). Although some articles considered site-specific settings such as community, location, and the main intended purpose of the recycled material (e.g., Ince et al., 2020), no articles were identified that discussed the recycling of mine tailings from the community perspective or the community involvement in the process. The lack of community investment in the development of mine tailings recycling processes is a significant omission, considering that the main goal of these recycling initiatives is the possible utilization of these products by the communities themselves

4. Discussion

For the purpose of this discussion, we select examples of ASM community applications from our literature review, namely, as road pavers through a community and as bricks used as part of a wall for home or industrial operation. In both cases, the material is exposed to environmental inputs, resulting in potential contaminant mobility through water, soil, and air. These ecological concerns directly link with health concerns which will also be addressed. To examine these applications more comprehensively, we adapted a risk assessment framework from the National Academy of Science and the U.S. EPA, as well as risk assessment characterizations from Watts (1998) and Maxwell (2014) that comprehensively consider the exposure assessment (i.e., pathway analysis) as applied to MRTAs that provides a conceptual basis for understanding the behavior of chemicals in different media. The Comprehensive Approach to Recycling Tailings (CART) framework seeks to incorporate the development of construction materials in ASM communities. This framework is divided into two main categories: (1) Hazard Identification and (2) Exposure Assessment. A comprehensive approach to mine tailings recycling is necessary as environmental media, the relationship between exposure pathways, and resulting health consequences are directly related to the community's basic needs, such as food and drinking sources. However, these tests are rarely done together, illustrating how previous studies only provided a snapshot of the potential environmental and health risks that MTRAs may pose.

Based on the scarcity of discussion regarding environmental, health, and social concerns associated with MTRAs, particularly with regards to ASM communities, this section discusses and explains the CART framework, considering the environmental and health aspects of using MTRAs in ASM communities and why they should be addressed prior to MTRA implementation. Although much of the emphasis on chemical exposure is on protecting health, assessing environmental contamination is a key activity in ensuring people's health.

Performing a full human and ecological risk assessment is not the goal of CART. However, what we are trying to achieve is to highlight holes in the source characterization and provide a discussion of the pathways that contaminants may take to reach receptors that need to be considered assuming a source of contamination is found. For a full risk assessment (National Academy Press, 1983; U.S. EPA, 1989) four steps are included: 1. Hazard identification; 2. Exposure assessment; 3. Toxicity assessment; and 4. Risk characterization. In this work, we are focusing on Steps 1 and 2 which are denoted in the bottom of Fig. 2, as well as some social considerations.

4.1. Hazard identification

Much uncertainty exists in the mobility of chemicals contained in MTRAs due to the lack of data available. Missing data includes the source (i.e., construction materials) concentration of heavy metals, possible applications, lack of due diligence when performing standard analysis, statistical analysis from results, and contamination pathways (e.g., soil, water, air). This uncertainty in the process and lack of information and data creates a problem when analyzing the identification of hazards to develop a risk assessment. Thus, the importance of this framework in helping ASM communities with giving them the required information in the proper stage of the process.

4.1.1. Source analysis (A)

The first step of the CART framework, Hazard Identification, determines the contaminants and chemicals present at the site and their characteristics, in this case, the mine tailings. As previously discussed, this step can utilize leaching tests, or analytical methods to determine the source concentrations, physical, and chemical properties of mine tailings, and concentrations of heavy metals in mine tailings helping characterize the material and products that are going to be part of the risk analysis. From the literature review, some MTRAs developed similar analyses to mine tailings to determine a baseline of heavy metals concentration that will be then used to compare the results of the exposure assessment.

Establishing baseline levels of heavy metals should be done in a manner that allows for quality assurance/quality control of standardized tests. The identified studies used numerous different protocols with which to identify heavy metals in samples, but they did not provide any information on how they verified their findings, nor the procedures developed to get to the results. In particular, researchers need to be aware of heterogeneities within the mine tailings themselves, including physical and chemical aspects (Yellishetty et al., 2008; W. Ju et al., 2017), ensuring that they have a representative sample to understand the baseline concentrations they are working with at the site.

Recommendations towards the use of standardized tests, triplication of samples, and quality assurance/quality control, can help develop better baselines that further research into the composition of mine tailings. Considerations such as site history and discussions with stakeholders can also help identify hazards and additional chemical elements that should be accounted for in the analysis of the contaminants present in mine tailings. Due to the chemical composition of mine tailings, a wide variety of heavy metals can be present. To properly identify potential hazards, concepts like Concentration-Toxicity Screening (U.S.

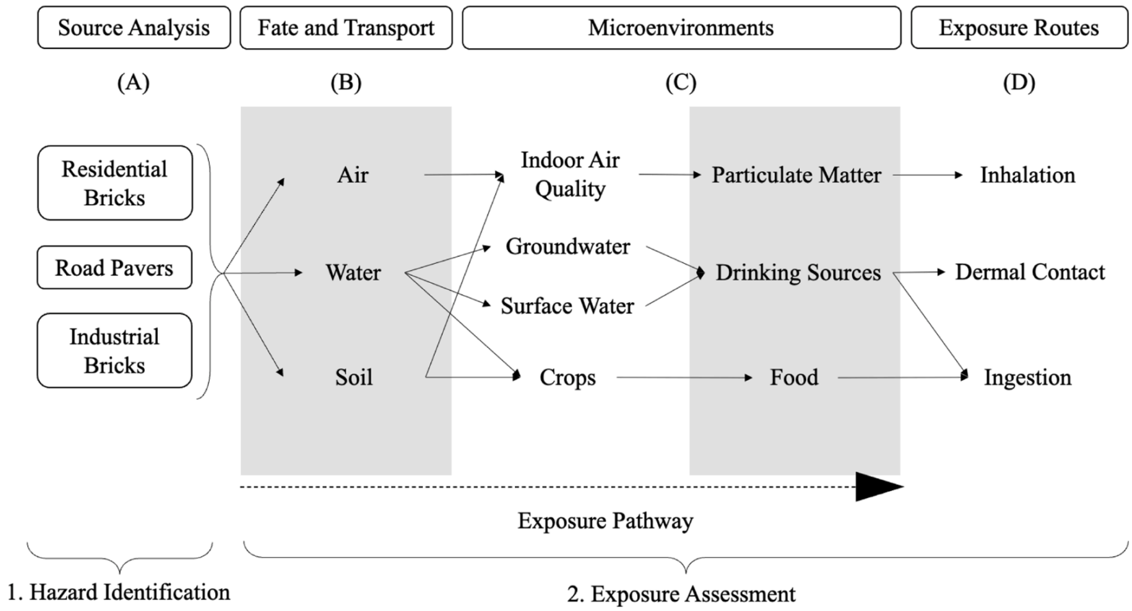

Fig. 2. Proposed comprehensive approach to recycling tailings (CART) framework for hazard identification and exposure assessment. Adapted from (National Academy Press, 1983; Watts, 1998; Maxwell, 2014).

EPA, 1989) can help identify chemicals that are more prone to contribute significantly to the risk of exposure by calculating individual scores that allow researchers select the most significant chemical elements for the analysis.

There are additional considerations that must be accounted for when applying this stage of the framework in ASM communities. In the case of ASGM, laboratory tests will need to include contaminants such as cyanide or mercury to account for the common processing techniques used at the sites. Additionally, ASM activities can often take place in remote areas (Seccatore et al., 2014), limiting site access and potentially leading to challenges with accessing laboratories for performing tests. Site access can be further restricted if miners are distrustful due to the illegality of their operations. One way to overcome this is to partner with organizations that can help in this process, whether it be NGOs that have already established a relationship with the community or local universities with access to laboratory equipment.

4.2. Exposure assessment

In the second step, Exposure Assessment, the transport of the identified contaminants in step one to receptors and levels of intake these receptors can have based on concentrations is analyzed. According to these fate and transport analyses, researchers and communities can consider possible negative impacts on the environment from the three main environmental media (i.e., water, soil, air) contributing to the decision-making process of stakeholders. In this section we will discuss the different components of the framework and their importance.

4.2.1. Fate and transport (B) and microenvironments (C)

In this section, the fate and transport (B) of contaminants through water, soil, and air are analyzed to determine their importance in the overall framework, what has been done, and the possible ways forward. Similarly, contaminant microenvironments (C) refer to the intersection of environmental aspects with health. As a key resource for mining operations and human consumption, water is an important element in this analysis. Mine water discharges or acid mine drainage (AMD), which is a solution with low pH and high concentration of metals and metalloids (Park et al., 2019) that is produced when sulfide-containing material are exposed to oxygen and water (Akcil and Koldas, 2006), have profound impacts in ecosystems and can severely contaminate soils, groundwater, and surface water (Peppas et al., 2000). Also, concerns are directed toward the use of water contaminated by ASM for agriculture and fish consumption due to the common use of mercury in ASM and the subsequent risk of bioaccumulation of methylmercury in fish. (Budnik and Casteleyn, 2019). To better characterize this, most MTRAs from the literature review have used test such as acid-base accounting (ABA), TCLP, and SPLP to determine acidic generation of materials (Bouzahzah et al., 2015). Such tests are readily available and can provide insights of the possible contaminants that can leach out of the construction materials, affecting people in the community and nearby bodies of water.

Nonetheless, water is then used by ASM communities to irrigate soils and crops that are then connected to health risks related to heavy metals intake through plants. Studies such as Armienta et al. (2020), where maize crops located in contaminated soils close to mine tailings exhibited small height and slow growth due to the intake and assimilation of heavy metals, show the importance of considering soil as a direct pathway of contaminants. Human plant consumption may pose an environmental and health risk, since high concentrations of contaminants may be readily available for uptake (Vamerali et al., 2010). From the literature review soils were not an important topic of concern for the analyzed MTRAs. To address this concern, the EPA has published a document that contains information regarding the use of selected analytical methods (SEM) to analyze contaminants of concern in environmental samples that come from remediation or contaminated sites (US EPA, 2017). This can help determine best analytical techniques depending on the environmental media analyzed such as soil and air (US EPA, 2017)(US EPA, 2017).

Particulate matter pollution can be detrimental to the environment and health, since suspended material in the air may subsequently get deposited in soils and bodies of water. The suspension of small particles is mostly done by the manipulation of mine tailings (e.g., mine tailings fabrication process, manipulation of material on-site, transport) as well as soils and environmental interactions such as wind or dry conditions (Moreno et al., 2007; Sims et al., 2013). As shown in other areas of research, just like asbestos, particulate matter may play an important role when analyzing health risk and environmental implications (Mossman et al., 1990). The possibility to suspend small particles that can transport contaminants through the air is an important factor that has been neglected when developing MTRAs. Although, no formal testing protocol is provided for conducting this analysis, indoor air quality models and particulate matter may serve as an option to address this issue. Furthermore, this activity may require different equipment for testing, and measuring which may not be available in ASM communities.

Despite the lack of details and information regarding the development and performance of the tests, in this review, we found one example that developed a more comprehensive approach that considered both environmental and human health risk assessments. This study showed that a combination of environmental testing, such as the SPLP, and health risk analysis can help determine the potential exposure route to contaminants. This article studies an interesting phenomenon where heavy metal leachability tests show the feasibility of using mine tailings for construction purposes while health risk assessment can prove the opposite. This may be attributed to the singular analysis of each separate heavy metal from the leachability tests, compared to the combine toxic effects of heavy metals in exposed individuals. This illustrates the importance of developing health risk assessments and combining results with intended MTRA applications by identifying where mine tailings products are used. Samples from this study showed that materials can impose carcinogenic risk to people at varying levels depending on their use in construction purposes (Ju et al., 2018). We recommend similar studies like Ju et al. (2018) to address both source and pathway (i.e., (B) and (C) sections in Fig. 2) analysis since studies like this provide a glimpse at the intersection of environmental concerns and health risks associated with the exposure routes of contaminants for people using these mine tailings construction materials. (See Fig. 2, for reference to the microenvironment section and the aspects considered).

4.2.2. Exposure routes (D)

When analyzing environmental impacts and risks associated with MTRAs, human health is prioritized since the health implications of mine tailings construction materials are closely related to the environmental concerns previously described (e.g., air-inhalation, soil and water-ingestion). For example, ingestion is directly influenced by the leachate and dust that can be produced when the mine tailings construction materials are exposed to weathering conditions. Exposure to construction materials is of particular concern for children due to their physical physiognomy (weight, size, and brain development) and the increased potential for exposure due to hand-to-mouth activities and other behaviors characteristic of their age (Cohen Hubal et al., 2000). Additionally, water and soil are the main concerns in this section since the microenvironments (C) in the CART framework are key for people's subsistence in these communities (drinking sources and food).

Similarly, inhalation is of concern when considering MTRAs that produce construction materials. Several researchers, including (Mwesigye et al., 2016; Nedic et al., 2019), have developed studies regarding the exposure to dust in different communities due to mining activities. Researchers such as McEwen et al. (2016) and Witten et al. (2019) have shown the possible health effects of inhaling dust. These studies acknowledge the importance of community awareness and traceability of contaminants from the mine site. Although few studies have focused on the possible exposure pathways that involve structures built from mine tailings (Hagan et al., 2013; McEwen et al., 2015), the researchers state the need for developing studies that calculate possible intake rates, indoor air quality, and exposure levels, to properly identify solutions or actions that help reduce the exposure to these contaminants in households. Additionally, inorganic mercury complexes may be present in dust or particulate matter released from construction materials which can then be inhaled by humans. According to Sholupov et al. (2004) about 80% of the mercury inhaled by humans remains in internal organs, which can adversely affect the brain, lungs, central and nervous system. Although there is no conclusive evidence of the link between mercury and cancer, kidney damage and immune system defects have been reported, as well as tremors, insomnia, memory loss, cognitive and motor dysfunctions, visual-field constriction, regional destruction of neurons and cerebellar granule cells (World Health Organization, 2007).

Considering the proposed applications in the CART framework (e.g. residential and industrial bricks), indoor air quality is of great importance since the probability of getting exposed to heavy metal concentrations increases in mining areas (Barbieri et al., 2014). A study conducted by the Environmental Health Council (2015) highlighted the relationship between exposures to a high concentration of heavy metals, such as mercury, and different environmental media (e.g., air, water, soil), showing the importance of considering dust and particulate matter when analyzing soils used in bricks for community purposes (Hagan et al., 2013; McEwen et al., 2016). Tools like the "Simulation tool kit for indoor air quality and inhalation exposure (IAQX)" may be the first approach to properly assess this problem, since modeling tools may offer an estimate of release rates that may affect people's health (National Risk Management Research Laboratory, 2000).

4.3. Social considerations

Despite the lack of information from the analyzed MTRAs regarding stakeholder engagement and community's risk perception, social considerations remain an important aspect that should be considered when examining the option of recycling mine tailings into construction materials. Although the social considerations are beyond the scope of this review, we acknowledge the importance of considering social aspects in the analysis of MTRAs from a community context standpoint.

Understanding the context of the communities may facilitate the transfer of knowledge and can also allow communities, researchers, and academics to properly address the community's needs that ultimately benefit the social dynamics within the same community. As proposed by Lucena et al. (2010) a community-centric approach of the Engineering and Sustainable Community Development (ESCD) model may enhance the development of projects and their sustainability in the future, as long as the community's self-determination and ownership of the projects exist. Similarly, a study developed by Wood et al. (2017) acknowledged the importance of educational efforts of implementing eco-friendly sanitation systems in communities. Efforts such as costs associated with implementation, how technologies work, intended purposes, and applications may help communities make informed decisions.

Unlike current approaches which lack community-centric activities, ESCD suggests the consideration of the following as applied to MTRAs:

- Listening to the community needs
  - The buy-in process of these construction materials in the community, as well as the relationship between economic benefits and the health of people willing to use these materials.
- Understanding social contexts
  - Economic cost associated with the fabrication of construction materials, making it feasible for ASM communities to implement.
  - The mass production of materials, and possibilities of ASM communities to produce these materials on their own.
  - Financial limitations for testing procedures.
- ASM communities' distrust in organizations
  - General levels of distrust from ASM communities towards external entities wanting to help with these kinds of projects due to their informal or illegal operations.
- Access to locations and services
  - Site access and geographical limitations.
  - Access to testing facilities and laboratories.
  - Difficult access to public health and health education programs.

These considerations can further help the implementation process in MTRAs, facilitating the adoption and application of construction materials from mine tailings in communities.

The development of the aforementioned framework can help communities, NGOs, academics, and researchers carry out MTRAs, assessing the environmental and health implications following the four steps explained above (i.e., Source Analysis, Fate and Transport, Microenvironments, Exposure Routes). The literature review has shown that many of the MTRAs developed have failed to incorporate environmental and health studies within their scope, making it hard for communities to evaluate the real impact of these projects in their lives. This framework aims to be the first tool that can be used to determine the feasibility of such projects (i.e., MTRA) in their community. The steps shown here are the result of the analysis of the literature and authors' knowledge about health and environmental topics. However, there are a number of caveats which concern the efficacy of the framework. When adapting these recommendations to ASM dynamics previously described such as site access, general levels of distrust due to ASM informal, semi-formalized or illegal operations, financial limitations for testing, access to testing facilities, or even who to ask for help, may represent an important source of uncertainty that will only be considered when analyzing each site individually, changing the dynamics of how the entities in charge of developing MTRAs operate and are accounted for.

5. Conclusions

Amid the worldwide outcry for the mining industry waste management policies, storage of mine tailings, and the impacts that these can have to the environment and people's health, mine tailings recycling has posed an interesting alternative to not just get rid of the possible contaminants within the mine tailings themselves but to generate alternative uses to this long-thought waste. As the popularity of mine tailings recycling continues to gain traction worldwide in ASM, there is a critical need to understand the environmental, health, and social risks associated with its recycling process to maintain the health and quality of life of ASM communities. This review synthesized information from 53 mine tailings recycling projects worldwide, both from academic and gray literature, and present a framework that can help understand and assess these environmental and health risks.

Findings suggest that although much progress has been made on the technical advancement of MTRAs, little attention has been provided to the consequences of such activity from environmental, health, and social perspectives. From the literature review we could determine that, technical contributions are mainly focused on production methods performed under laboratory conditions, such as geopolymerization and mixture with Ordinary Portland Cement. Final application of the recycled mine tailings is rarely discussed, with only 6 studies describing the main fabricated products.

Studies on the development of MTRAs provide a piecemeal strategy for environmental assessment, mainly focusing on limited leaching procedure tests. Other important aspects of environmental risk assessment were absent from existing studies. Only one study to date integrated public health and environmental knowledge, helping illustrate the possible carcinogenic and non-carcinogenic risks that heavy metal contamination may present via different exposure routes.

Prior to implementation in ASM communities, potential hazards to public health and the environment require consideration. Thus, a Comprehensive Approach to Recycling Tailings (CART) framework is proposed to assist in potential hazard identification and exposure assessment of MTRAs. The purpose of this framework is to highlight additional environmental and health considerations prior to using MTRAs for various construction materials and especially final use. Additional studies should be made from the source (e.g., houses, roads) to the potential exposure from the perspective of inhalation, ingestion, and dermal contact. When applied to communities in developing countries, this integration requires community participation to better understand the processing and usage within the community rather than the current focus of methods develop under controlled conditions, as seen in the literature review with lab-scale construction materials fabrication tests.

If the success of ASM is to have place, we need action tools that allow stakeholders to properly give an assessment on the feasibility of using MTRAs to decrease further contamination from mine tailings. Although not definitive and immutable, this framework can help elucidate methods, actions, or analyses that can be done to these construction materials to understand the impacts in water, soil, air, and the interaction of these environmental media to the community's surroundings and activities, ultimately giving necessary knowledge to prevent health risks and the environmental harm. As such, this framework is written to allow for site-specific characteristics to influence the overall design and implementation of an MTRA projects. This framework leaves the door open for future research in the topic from environmental, public health, and social fields to increase the knowledge base and create an even more comprehensive framework.

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References

Ahmari, S., Zhang, L., 2012. Production of eco-friendly bricks from copper mine tailings through geopolymerization. Constr. Build. Mater. 29, 323–331. https://doi.org/10.1016/j.conbuildmat.2011.10.048.

Akcil, A., Koldas, S., 2006. Acid Mine Drainage (AMD): causes, treatment and case studies. J. Clean. Prod. 14 (12–13), 1139–1145. https://doi.org/10.1016/j.jclepro.2004.09.006. SPEC. ISS.Elsevier.

Argane, R., Benzaazoua, M., Bouamrane, A., Hakkou, R., 2015. Cement hydration and durability of low sulfide tailings-based renders: a case study in Moroccan constructions. Miner. Eng. 76, 97–108. https://doi.org/10.1016/j.mineng.2014.10.022.

Argane, R., Benzaazoua, M., Hakkou, R., Bouamrane, A., 2016. A comparative study on the practical use of low sulfide base-metal tailings as aggregates for rendering and masonry mortars. J. Clean. Prod. 112, 914–925. https://doi.org/10.1016/j.jclepro.2015.06.004.

Argane, R., el Adnani, M., Benzaazoua, M., Bouzahzah, H., Khalil, A., Hakkou, R., Taha, Y., 2016. Geochemical behavior and environmental risks related to the use of abandoned base-metal tailings as construction material in the upper-Moulouya district, Morocco. Environ. Sci. Pollut. Res. 23 (1), 598–611. https://doi.org/10.1007/s11356-015-5292-y.

Armienta, M.A., Beltrán, M., Martínez, S., Labastida, I., 2020. Heavy metal assimilation in maize (Zea mays L.) plants growing near mine tailings. Environ. Geochem. Health 42 (8), 2361–2375. https://doi.org/10.1007/s10653-019-00424-1.

Aseniero, J.P.J., Opiso, E.M., Banda, M.H.T., Tabelin, C.B., 2019. Potential utilization of artisanal gold-mine tailings as geopolymeric source material: preliminary investigation. SN Appl. Sci. 1 (1), 35. https://doi.org/10.1007/s42452-018-0045-4.

Aznar-Sánchez, J.A., García-Gómez, J.J., Velasco-Muñoz, J.F., Carretero-Gómez, A., 2018. Mining waste and its sustainable management: advances in worldwide research. Minerals 8 (7). https://doi.org/10.3390/min8070284.

Barbieri, E., Fontúrbel, F.E., Herbas, C., Barbieri, F.L., Gardon, J., 2014. Indoor metallic pollution and children exposure in a mining city. Sci. Total Environ. 487, 13–19. https://doi.org/10.1016/j.scitotenv.2014.03.136.

Beltrán-Rodríguez, L.N., Larrahondo, J.M., Cobos, D., 2018. Tecnologías emergentes para disposición de relaves: oportunidades en Colombia. Bol. Cienc. Tierra 44, 5–20. https://doi.org/10.15446/rbct.n44.66617.

Boholm, Å., 2003. The cultural nature of risk: can there be an anthropology of uncertainty? Ethnos 68 (2), 159–178. https://doi.org/10.1080/0014184032000097722.

Bouzahzah, H., Benzaazoua, M., Plante, B., Bussiere, B., 2015. A quantitative approach for the estimation of the "fizz rating" parameter in the acid-base accounting tests: a new adaptations of the Sobek test. J. Geochem. Explor. 153, 53–65. https://doi.org/10.1016/j.gexplo.2015.03.003.

Buch, A.C., Niemeyer, J.C., Marques, E.D., Silva-Filho, E.V., 2021. Ecological risk assessment of trace metals in soils affected by mine tailings. J. Hazard. Mater. 403, 123852 https://doi.org/10.1016/j.jhazmat.2020.123852.

Budnik, L.T., Casteleyn, L., 2019. Mercury pollution in modern times and its socio-medical consequences. Sci. Total Environ. 654, 720–734. https://doi.org/10.1016/j.scitotenv.2018.10.408.

Byrne, P., Hudson-Edwards, K., Macklin, M., Brewer, P., Bird, G., Williams, R., Byrne, P., Hudson-Edwards, K., Macklin, M., Brewer, P., Bird, G., Williams, R., 2015. The Long-Term Environmental Impacts of the Mount Polley Mine Tailings Spill, 17. British Columbia, Canada. EGUGA. https://ui.adsabs.harvard.edu/abs/2015EGUGA..17.6241B/abstract.

Cárdenas Ticlavilca, F.J., 2019. Propuesta De Uso De Relaves De Mina Polimetálica En La Fabricación De Unidades De Albañilería - caso ex Unidad Minera Mercedes 3. Universidad Peruana de Ciencias Aplicadas. https://doi.org/10.19083/tesis/625225.

Chen, T.J., Zhang, Y.M., Jiao, X.K., Liu, T., 2012. Research on preparation and performance of vandium tailings-based geopolymer. 26th International Mineral Processing Congress, IMPC 2012: Innovative Processing for Sustainable Growth - Conference Proceedings 139, 830–838.

Cohen Hubal, E.A., Sheldon, L.S., Burke, J.M., McCurdy, T.R., Berry, M.R., Rigas, M.L., Zartarian, V.G., Freeman, N.C, 2000. Children's exposure assessment: a review of factors influencing Children's exposure, and the data available to characterize and assess that exposure. Environ. Health Perspect. 108 (6), 475–486. https://doi.org/10.1289/ehp.108-1638158.

dos Santos, T.G., Ribeiro Martins, L.F., Rodriguez Sosa, E., 2019. Technological characterization of tailings from iron and gold mining with a geoenvironmental focus for reuse in geotechnical application. Environmental Science and Engineering, pp. 253–260 https://doi.org/10.1007/978-981-13-2227-3_31.

Fernández-Bertran, J.F., 1999. Mechanochemistry: an overview. Pure Appl. Chem. 71 (4), 581–586. https://doi.org/10.1351/pac199971040581.

Global Tailings Review. (2020). Global Industry Standard on Tailings Management. https://globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard_EN.pdf.

Hagan, N., Robins, N., Gonzales, R.D.E., Hsu-Kim, H., 2015. Speciation and bioaccessibility of mercury in adobe bricks and dirt floors in Huancavelica, Peru. Environ. Geochem. Health 37 (2), 263–272. https://doi.org/10.1007/s10653-014-9644-1.

Hagan, N., Robins, N., Hsu-Kim, H., Halabi, S., Espinoza Gonzales, R.D., Richter, D.deB., Vandenberg, J., 2013. Residential mercury contamination in adobe brick homes in Huancavelica, Peru. PLoS ONE 8 (9), 9. https://doi.org/10.1371/journal.pone.0075179.

Hilson, G., Van Bockstael, S., Sauerwein, T., Hilson, A., McQuilken, J., 2021. Artisanal and small-scale mining, and COVID-19 in sub-Saharan Africa: a preliminary analysis. World Dev. 139, 105315 https://doi.org/10.1016/j.worlddev.2020.105315.

Ince, C., Derogar, S., Gurkaya, K., Ball, R.J., 2020. Properties, durability and cost efficiency of cement and hydrated lime mortars reusing copper mine tailings of Lefke-Xeros in Cyprus. Constr. Build. Mater., 121070 https://doi.org/10.1016/j.conbuildmat.2020.121070.

van Jaarsveld, J.G.S., Lukey, G.C., van Deventer, J.S.J., Graham, A., 2000. The stabilisation of mine tailings by reactive geopolymerisation. MINPREX 2000 363–371. *September*.

Johnson, D.B., Hallberg, K.B., 2005. Acid mine drainage remediation options: a review. Sci. Total Environ. 338 (1–2), 3–14. https://doi.org/10.1016/j.scitotenv.2004.09.002.

Ju, W.J., Hwang, S.K., Jho, E.H., Nam, K., 2018. Determining the reuse of metal mine wastes based on leaching test and human health risk assessment. Environ. Eng. Res. 24 (1), 82–90. https://doi.org/10.4491/eer.2017.211.

Ju, W., Shin, D., Park, H., Nam, K., 2017. Environmental compatibility of lightweight aggregates from mine tailings and industrial byproducts. Metals (Basel) 7 (10), 390. https://doi.org/10.3390/met7100390.

Kan, X., Dong, Y., Feng, L., Zhou, M., Hou, H., 2021. Contamination and health risk assessment of heavy metals in China's lead-zinc mine tailings: a meta-analysis. Chemosphere 267, 128909. https://doi.org/10.1016/j.chemosphere.2020.128909.

Kiventerä, J., Lancellotti, I., Catauro, M., Poggetto, F.D., Leonelli, C., Illikainen, M., 2018. Alkali activation as new option for gold mine tailings inertization. J. Clean. Prod. 187, 76–84. https://doi.org/10.1016/j.jclepro.2018.03.182.

Komnitsas, K., Zaharaki, D., 2007. Geopolymerisation: a review and prospects for the minerals industry. Miner. Eng. 20 (14), 1261–1277. https://doi.org/10.1016/J.MINENG.2007.07.011.

Lottermoser, B.G., 2011. Recycling, reuse and rehabilitation of mine wastes. Elements 7 (6), 405–410. https://doi.org/10.2113/gselements.7.6.405.

Lu, C.-C., Hsu, M.H., Lin, Y.-P., 2019. Evaluation of heavy metal leachability of incinerating recycled aggregate and solidification/stabilization products for construction reuse using TCLP, multi-final pH and EDTA-mediated TCLP leaching tests. J. Hazard. Mater. 368, 336–344. https://doi.org/10.1016/j.jhazmat.2019.01.066.

Lucena, J., Schneider, J., Leydens, J.A., 2010. Engineering and sustainable community development. Synth. Lect. Eng. Technol. Soc. 5 (1), 1–230. https://doi.org/10.2200/S00247ED1V01Y201001ETS011.

Lucena, J., Schneider, J., Leydens, J.A., 2011. Making the human dimensions of sustainable community development visible to engineers. Proc. Inst. Civ. Eng.: Eng. Sustain. 164 (1), 13–23. https://doi.org/10.1680/ensu.1000014.

Mabroum, S., Moukannaa, S., el Machi, A., Taha, Y., Benzaazoua, M., Hakkou, R., 2020. Mine wastes based geopolymers: a critical review. Cleaner Engineering and Technology III, 100014. https://doi.org/10.1016/j.clet.2020.100014.

Mahmood, A.A., Elektorowicz, M., 2020. An investigation of the porosity dependent strength and leachability of mine tailings matrices containing heavy metals. Cogent Environ. Sci. 6 (1) https://doi.org/10.1080/23311843.2020.1743626.

Maxwell, N.I., 2014. Understanding environmental health: how we live in the world. Understanding Environmental health: How we Live in the World, 2nd Edi. http://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=psyc6&NEWS=N&AN=2008-04069-000.

McDonald, J.E.D., Roache, S.C., Kawatra, S.K., 2016. Repurposing mine tailings: cold bonding of siliceous iron ore tailings. Miner. Metall. Process. 33 (1), 47–52. https://doi.org/10.19150/mmp.6467.

McEwen, A.R., Hsu-Kim, H., Robins, N.A., Hagan, N.A., Halabi, S., Barras, O., Richter, D. deB., Vandenberg, J.J., 2016. Residential metal contamination and potential health risks of exposure in adobe brick houses in Potosí, Bolivia. Sci. Total Environ. 562, 237–246. https://doi.org/10.1016/j.scitotenv.2016.03.152.

McEwen, A.R., Hsu-Kim, H., Vandenber, J.J., 2015. Potential health risks of trace elements in adobe brick houses in a historical mining town: potosí, Bolivia [Duke University]. European University Institute. https://eur-lex.europa.eu/legal-content/PT/TXT/PDF/?uri=CELEX:32016R0679&from=PT%0Ahttp://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52012PC0011:pt:NOT.

Mohajerani, A., Suter, D., Jeffrey-Bailey, T., Song, T., Arulrajah, A., Horpibulsuk, S., Law, D., 2019. Recycling waste materials in geopolymer concrete. Clean Technol. Environ. Policy 21 (3), 493–515. https://doi.org/10.1007/s10098-018-01660-2.

Moreno, T., Oldroyd, A., McDonald, I., Gibbons, W., 2007. Preferential fractionation of trace metals–metalloids into PM10 resuspended from contaminated gold mine tailings at Rodalquilar, Spain. Water Air Soil Pollut. 179 (1–4), 93–105. https://doi.org/10.1007/s11270-006-9216-9.

Mossman, B.T., Bignon, J., Corn, M., Seaton, A., Gee, J.B.L., 1990. Asbestos: scientific developments and implications for public policy. Science 247 (4940), 294–301. https://doi.org/10.1126/science.2153315.

Muleya, F., Mulenga, B., Zulu, S.L., Nwaubani, S., Tembo, C.K., Mushota, H., 2020. Investigating the suitability and cost-benefit of copper tailings as partial replacement of sand in concrete in Zambia: an exploratory study. J. Eng. Des. Technol. https://doi.org/10.1108/JEDT-05-2020-0186.

Mwesigye, A.R., Young, S.D., Bailey, E.H., Tumwebaze, S.B., 2016. Population exposure to trace elements in the Kilembe copper mine area, Western Uganda: a pilot study. Sci. Total Environ. 573, 366–375. https://doi.org/10.1016/j.scitotenv.2016.08.125.

National Academies of Sciences, Engineering, and M., 2009. Science and decisions. Science and Decisions: Advancing Risk Assessment. National Academies Press. https://doi.org/10.17226/12209.

National Academy Press. (1983). Risk Assessment in the Federal Government: managing the Process.

National Risk Management Research Laboratory. (2000). *Simulation tool kit for indoor air quality and inhalation exposure (IAQX), user guide* (1.0; Issue October). https://nepis.epa.gov/Adobe/PDF/P1000A0G.pdf.

Nedic, A., Pucarevic, M., Ninkov, J., Stojic, N., Milic, D., 2019. Mercury content and distribution in household dust and soil in the town of Sid. Zbornik Matice Srpske Za Prirodne Nauke 4 (137), 33–41. https://doi.org/10.2298/ZMSPN1937033N.

O'Brien, R.M., Phelan, T.J., Smith, N.M., Smits, K.M., 2020. Remediation in developing countries: a review of previously implemented projects and analysis of stakeholder participation efforts. Crit. Rev. Environ. Sci. Technol. 0 (0), 1–22. https://doi.org/10.1080/10643389.2020.1755203.

Ongley, E.D., Booty, W.G., 1999. Pollution remediation planning in developing countries. Water Int. 24 (1), 31–38. https://doi.org/10.1080/02508069908692131.

Owen, J.R., Kemp, D., 2019. Displaced by mine waste: the social consequences of industrial risk-taking. Extr. Ind. Soc. 6 (2), 424–427. https://doi.org/10.1016/j.exis.2019.02.008.

Park, I., Tabelin, C.B., Jeon, S., Li, X., Seno, K., Ito, M., Hiroyoshi, N., 2019. A review of recent strategies for acid mine drainage prevention and mine tailings recycling. Chemosphere 219, 588–606. https://doi.org/10.1016/j.chemosphere.2018.11.053.

Pedersen, A.F., Nielsen, J.Ø., Friis, C., Jønsson, J.B., 2021. Mineral exhaustion and its livelihood implications for artisanal and small-scale miners. Environ. Sci. Policy 119, 34–43. https://doi.org/10.1016/j.envsci.2021.02.002.

Peppas, A., Komnitsas, K., Halikia, I., 2000. Use of organic covers for acid mine drainage control. Miner. Eng. 13 (5), 563–574. https://doi.org/10.1016/S0892-6875(00)00036-4.

Perry, P.M., Pavlik, J.W., Sheets, R.W., Biagioni, R.N., 2005. Lead, cadmium, and zinc concentrations in plaster and mortar from structures in Jasper and Newton Counties, Missouri (Tri-State Mining District). Sci. Total Environ. 336 (1–3), 275–281. https://doi.org/10.1016/j.scitotenv.2004.07.007.

Petkovic, G., Engelsen, C.J., Håøya, A.-O., Breedveld, G., 2004. Environmental impact from the use of recycled materials in road construction: method for decision-making in Norway. Resour. Conserv. Recycl. 42 (3), 249–264. https://doi.org/10.1016/j.resconrec.2004.04.004.

Maray, Radio, 2019. Mujer Impacta Atacama Produce Eco-Adoquines Con Relaves Mineros. https://www.maray.cl/2019/05/16/mujer-impacta-atacama-produce-eco-adoquines-con-relaves-mineros/.

Ricardo, A.A., Barbosa, S.R.M., Costa, N.P., Rodrigues, L.M., Galery, R., Mazzinghy, D.B., 2019. Economia Circular: Desenvolvimento de Cimento Ecológico Usando Rejeitos De Minério De Ferro. XXVIII Encontro Nacional de Tratamento de Minérios e Metalurgia Extrativa. http://www.entmme2019.entmme.org/trabalhos/104.pdf.

Roy, S., Adhikari, G.R., Gupta, R.N., 2007. Use of gold mill tailings in making bricks: a feasibility study. Waste Manag. Res. 25 (5), 475–482. https://doi.org/10.1177/0734242X07076944.

Saedi, A., Jamshidi-Zanjani, A., Darban, A.K., 2020. A review on different methods of activating tailings to improve their cementitious property as cemented paste and reusability. J. Environ. Manage. 270, 110881 https://doi.org/10.1016/j.jenvman.2020.110881. February.

Schwartz, M., Smits, K., Smith, J., Phelan, T., Restrepo Baena, O.J., 2021. Incorporating positive deviance into comprehensive remediation projects: a case study from artisanal and small-scale gold mining in the municipality of Andes, Colombia. Environ. Sci. Policy 123, 142–150. https://doi.org/10.1016/j.envsci.2021.05.021. January.

Seccatore, J., Veiga, M., Origliasso, C., Marin, T., De Tomi, G., 2014. An estimation of the artisanal small-scale production of gold in the world. Sci. Total Environ. 496, 662–667. https://doi.org/10.1016/j.scitotenv.2014.05.003. October.

SENA. (2020). *Desarrollo de materiales de la industria de la construccion a partir de suelos degradados y relaves mineros, como parte del proceso de reconversion laboral en el Bajo Cauca.*

Sholupov, S., Pogarev, S., Ryzhov, V., Mashyanov, N., Stroganov, A., 2004. Zeeman atomic absorption spectrometer RA-915+ for direct determination of mercury in air and complex matrix samples. Fuel Process. Technol. 85, 473–485. https://doi.org/10.1016/j.fuproc.2003.11.003.

Silva Rotta, L.H., Alcântara, E., Park, E., Negri, R.G., Lin, Y.N., Bernardo, N., Mendes, T.S. G., Souza Filho, C.R., 2020. The 2019 Brumadinho tailings dam collapse: possible cause and impacts of the worst human and environmental disaster in Brazil. Int. J. Appl. Earth Obs. Geoinf. 90, 102119 https://doi.org/10.1016/j.jag.2020.102119.

Sims, D.B., Hooda, P.S., Gillmore, G.K., 2013. Mining activities and associated environmental impacts in arid climates: a literature review. Environ. Pollut. 2 (4) https://doi.org/10.5539/ep.v2n4p22.

Sobolev, K., 2005. Mechano-chemical modification of cement with high volumes of blast furnace slag. Cem. Concr. Compos. 27 (7–8), 848–853. https://doi.org/10.1016/j.cemconcomp.2005.03.010.

Taha, Y., Benarchid, Y., Benzaazoua, M., 2019. Environmental behavior of waste rocks based concrete: leaching performance assessment. Resour. Policy, 101419. https://doi.org/10.1016/j.resourpol.2019.101419.

The Environmental Health Council, 2015. Remedial Investigation, Huancavelica Mercury Remediation Project. http://www.ehcouncil.org/eng/files/2016/03/RI-english-1.pdf.

Tirima, S., Bartrem, C., von Lindern, I., von Braun, M., Lind, D., Anka, S.M., Abdullahi, A., 2016. Environmental Remediation to Address Childhood Lead Poisoning Epidemic due to Artisanal Gold Mining in Zamfara, Nigeria. Environ. Health Perspect. 124 (9), 1471–1478. https://doi.org/10.1289/ehp.1510145.

U.S. EPA. (1989). *Risk assessment guidance for superfund volume I human health evaluation manual (Part A)*. https://www.epa.gov/risk/risk-assessment-guidance-superfund-rags-part.

US EPA. (2017). Selected analytical methods for environmental remediation and recovery (SAM) - 2017. In U.S. Environmental Protection Agency (Issue September). https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NHSRC&dirEntryId=339252.

Vamerali, T., Bandiera, M., Mosca, G., 2010. Field crops for phytoremediation of metal-contaminated land. A review. Environ. Chem. Lett. 8 (1), 1–17. https://doi.org/10.1007/s10311-009-0268-0.

Vargas, F., Lopez, M., Rigamonti, L., 2020. Environmental impacts evaluation of treated copper tailings as supplementary cementitious materials. Resour. Conserv. Recycl. 160, 104890 https://doi.org/10.1016/j.resconrec.2020.104890.

Veiga, M.M., Hinton, J.J., 2002. Abandoned artisanal gold mines in the Brazilian Amazon: a legacy of mercury pollution. Nat. Resour. Forum 26 (1), 15–26. https://doi.org/10.1111/1477-8947.00003.

Veiga, M.M., Marshall, B.G., 2019. The Colombian artisanal mining sector: formalization is a heavy burden. Extr. Ind. Soc. 6 (1), 223–228. https://doi.org/10.1016/j.exis.2018.11.001.

Watts, R.J., 1998. Hazardous Waste Risk Assessment. Hazardous Wastes: Sources, Pathways, Receptors. John Wiley & Sons, INC, pp. 518–537.

Witten, M.L., Chau, B., Sáez, E., Boitano, S., Clark Lantz, R., 2019. Early life inhalation exposure to mine tailings dust affects lung development. Toxicol. Appl. Pharmacol. 365, 124–132. https://doi.org/10.1016/J.TAAP.2019.01.009.

Wood, A., Blackhurst, M., Lawler, D.F., 2017. Will U.S. Homeowners Adopt Eco-Toilets? J. Environ. Eng. 143 (6), 05017002 https://doi.org/10.1061/(ASCE)EE.1943-7870.0001204.

Bank, World, 2020. 2020 State of the Artisanal and Small-Scale Mining Sector. Exposure to Mercury: A Major public Health Concern https://delvedatabase.org/resources/2020-state-of-the-artisanal-and-small-scale-mining-sectorWorld Health Organization (2007). https://www.who.int/ipcs/features/mercury.pdf.

Xu, D.-M., Zhan, C.-L., Liu, H.-X., Lin, H.-Z., 2019. A critical review on environmental implications, recycling strategies, and ecological remediation for mine tailings. Environ. Sci. Pollut. Res. 26 (35), 35657–35669. https://doi.org/10.1007/s11356-019-06555-3.

Yellishetty, M., Karpe, V., Reddy, E.H., Subhash, K.N., Ranjith, P.G., 2008. Reuse of iron ore mineral wastes in civil engineering constructions: a case study. Resour. Conserv. Recycl. 52 (11), 1283–1289. https://doi.org/10.1016/j.resconrec.2008.07.007.