ENVIRONMENTAL AND HEALTH IMPLICATIONS OF MINE TAILING-BASED CONSTRUCTION MATERIALS IN DEVELOPING COMMUNITIES: CURRENT PRACTICES AND WAYS FORWARD

By

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ABSTRACT

For many years, artisanal and small-scale mining (ASM) communities around the world have been developing strategies to reduce contaminated mine tailings produced by mineral processing operations. These mine tailings are the by-product of the physical and chemical processes required to extract metals that humans require every day. The strategies developed by these communities cover a wide range of solutions, such as better practices in mineral processing activities as well as alternative technologies that help reduce the environmental impact of mining. Specifically, the recycling of mine tailings to produce construction materials has been of interest to researchers and communities.

The use of mine tailings for construction purposes has been documented in more than ten countries around the world, including Colombia, Peru, Bolivia, China, the United States, the Philippines, and Morocco. Although community efforts exist to recycle mine tailings into construction materials, most of these efforts have fallen short in addressing the environmental and health concerns that are created from the potential exposure to heavy metal contamination. This thesis aims to analyze the environmental and health aspects of mine tailings used for construction purposes by considering the studies developed by researchers, communities, and other organizations on this topic. In addition, limited social considerations are addressed in an effort to identify some key aspects from a community perspective. Possible impacts of using mine tailings as construction materials to the environment and human health are also discussed from a community engagement perspective.

Results show that mine tailings recycling activities (MTRAs) are generally focused on fabrication methods with an emphasis on the use of geopolymers and Ordinary Portland Cement (OPC) to produce construction materials. These construction materials consist mostly in bricks,

pavers, and mortars, with a little emphasis in applications and final use. Environmental impact assessments are done by testing for heavy metal contamination using toxicity leaching tests such as the Toxicity Characteristic Leaching Procedure (TCLP) and other methods to determine the concentration of heavy metals in mine tailings and products. Health and social considerations are often overlooked in the process, lacking stakeholder perspectives and a comprehensive approach.

To understand the recycling of mine tailings into construction materials from a more holistic perspective, a Comprehensive Approach to Recycling Tailings (CART) framework is proposed. This framework is adapted from the Environmental Protection Agency (EPA) risk assessment procedure, and it proposes environmental and public health analyses that open possible avenues for future research in the recycling of mine tailings. Additionally, this framework illustrates social factors, which include the perception of risk that communities may have regarding the utilization of mine tailing-based-construction materials, as well as the gap that exists between the technical knowledge developed by researchers and the possible implementation in communities (i.e., research translation), stakeholder awareness, and community's buy-in.

The dissemination work carried out in this thesis focuses mostly on developing activities that help communities understand these recycling initiatives and consider additional aspects such as the environment, people's health, and community perception. This educational outreach includes the understanding of proper methods to deem these construction materials safe, as well as social considerations needed to properly implement mine tailing recycling in communities around the world.

Finding from this research will contribute to better assess mine tailing recycling activities from an ecological and public health perspective, by highlighting current methods developed worldwide and giving a different approach to the recycling of mine tailings. Researchers, academics, and people seeking to pursue these recycling activities may find a toolkit to develop a more comprehensive approach that allows them to give technical and scientific credibility to these mine-tailing recycled products. It will also contribute to the advancement of the communication between the scientific community and society to better tailor future initiatives to the community's needs and desires.

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to the best parents, José R. Velásquez and María O. Vásquez

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LIST OF ABBREVIATIONS

ABA – Acid-base accounting

ADI – Average daily intake

AMD – Acid mine drainage

ASGM – Artisanal and small-scale gold mining

ASM – Artisanal and small-scale mining

CART – Comprehensive approach to recycle tailings

ESCD – Engineering and sustainable community development

HQ – Hazard Quotient

IAQX – Indoor air quality and inhalation exposure simulation tool kit

ICPMS - Inductively coupled plasma mass spectrometry

LSM – Large scale mining

MTR – Mine tailing recycling

MTRAs – Mine tailing recycling activities

NAS – National Academy of Science, Engineering, and Medicine

NGOs – Non-governmental organizations

OPC – Ordinary Portland cement

RfD – Reference dose

SPLP – Synthetic precipitation leaching procedure

TCLP – Toxicity characteristics leaching procedure

US EPA – United States Environmental Protection Agency

XRF – X-ray fluorescence

CHAPTER 1 - INTRODUCTION

1.1 Background

The mining industry produces more than 65 billion tons of waste annually, of which 14 billion tons are waste generated by mineral processing (Jones & Boger, 2012). This waste, also known as mine tailings, is fine material produced by the intensive crushing and milling of rocks to expose the mineral to chemical substances used to extract metals. This process only extracts the desired metals and discards all other metals that are not required, including arsenic, lead, copper, nickel, cadmium (Rankin, 2017). Tailings are then dumped in impoundments or bags to then be placed in piles, often near bodies of water and residential centers. Mine waste disposal issues cover a wide variety of fields in the mining sector, including pollution and environmental concerns, legal regulation, and human health issues (Adiansyah et al., 2015).

Artisanal and Small-Scale Mining (ASM) communities have tried to develop alternatives to improve environmental impacts generated by their operations (Schwartz et al., 2021). However, these alternatives often lack technical input and fall short of addressing root problems such as mercury emission and water and soil contamination. As stated by Schwartz et al. (2021), communities' own grassroots initiatives are important to properly address implementation issues and long-term adoption in these mining communities. However, most of these initiatives do not address common concerns such as weathering risks, physical strength characteristics (Mahmood & Elektorowicz, 2015), and health aspects (Candeias et al., 2019). These concerns are of high relevance due to the heavy metal contamination and the mobility associated with these contaminants through the environment and food chain, as well as the health implications of heavy metal exposure for people living in these areas. Communities, researchers, and academics looking for sustainable practices and reuse of waste in the mining industry have utilized disciplines such as material science, chemistry, and mechanical engineering to recycling mine waste for construction purposes, showing feasible results in the reuse of mine tailings as construction materials (Ahmari et al., 2012; Ahmari & Zhang, 2012; Argane et al., 2015; Kiventerä et al., 2016; Park et al., 2019; Roy et al., 2007). Although mine waste recycling practices could improve the environmental perception of mining and the sustainability of the industry (Aznar-Sánchez et al., 2018), not all implications have been properly addressed. The environmental, health, and social impacts have not been thoroughly studied nor incorporated into mine tailings recycling practices.

Effective and sustainable recycling of mine tailings requires the use of multidisciplinary approaches that comprehensively look at this activity (Aznar-Sánchez et al., 2018). The technical repurposing process must be well understood and executed to ensure the creation of strong, leaching-resistant, and economically feasible construction materials. Environmental testing protocols and health risk assessments are necessary to ensure that contaminated mining waste does not pose a risk to humans or the environment (Maboeta et al., 2018; Plumlee & Morman, 2011; World Health Organization, 2007). Stakeholder engagement, namely two-way knowledge transfer, may create better-informed communities with increased buy-in and decision-making power; this could result in improved abilities to assess and adopt projects that can meaningfully improve quality of life (Wood et al., 2017). To do so, information and knowledge sharing are required to benefit community members. However, this knowledge and information is not readily available to communities or is published in non-open-access portals that cannot be accessed by these community members, generating a gap between the knowledge that is being produced and the possible implementation of this knowledge in communities. Each one of the aforementioned critical elements has been studied separately and has not been considered as a codependent variable in a sequence of steps that may help communities develop inclusive projects based on an environmental and sustainability framework.

The purpose of this work is to analyze both the environmental and health, implications of previous mine tailing recycling initiatives, identifying possible ways forward to incorporate the environmental, health, and social aspects from a more comprehensive approach. Results can serve as a reference for future initiatives in mining communities and as a proposed methodology to ensure that information regarding these initiatives is better assessed and widely disseminated. In this work, the risk perception by communities is also studied under a knowledge transfer process between research and community participation.

1.2 Research Objectives

The overarching purpose of this work is to improve the long-term applicability of mine tailings recycling in developing communities by understanding current trends and identifying existing holes in the literature that can help improve the assessment of future projects in ASM communities. To accomplish this objective, this works seeks to address three research questions:

- How are environmental and health implications currently addressed in the recycling of mine tailings for construction purposes?
- In what ways can environmental and health concerns be integrated into the development of these recycling activities?
- What social considerations need to be made to help in the community engagement and knowledge transfer processes?

The first research question addresses the state of the art in the recycling efforts of mine tailings for construction materials in developing communities worldwide, looking with special emphasis to the environmental and health implications in the recycling activity. The second research question synthesized the previous research questions and propose possible ways forward in the integration of the environmental and health aspects required in the recycling process. The third research question focuses on the transfer of the previously gathered knowledge to help people seeking sustainability in these types of projects. The last question was approached from two perspectives: (1) The perception of risk that people in these communities may have regarding the use of heavy metal-laden tailings for construction purposes, and (2) appropriate methods of transferring knowledge that can better inform communities of these processes.

In order to address these questions, this work requires the review of published and grey literature, the analysis of studies under an environmental and health perspective to determine the tests, activities, and actions developed by researchers, communities, universities, and NGOs in the field of mine tailings recycling. Then an analysis based on an environmental and health risk assessment is carried out to determine key aspects that can help in the implementation of these construction materials in communities. A framework is proposed to integrate key environmental and health aspects into the development of recycling activities. Outreach to contacts in Latin America, experiences from the field, and literature have helped in the development of proper knowledge transfer to these communities that these construction materials seek to serve. Also, this work seeks to satisfy two important research objectives:

Objective 1 – To review and analyze previous works on the recycling of mine tailings in the light of environmental and health risk assessments to develop a more comprehensive approach that allows communities to assess these initiatives more holistically.

Objective 2 – Determine the best way to disseminate findings to community members (e.g., miners and the general public) by considering stakeholder engagement and community needs.

Findings from this research will contribute to a better and improved assessment of the construction materials by considering the environmental and health implications of recycling mine tailings into construction materials. People interested in these initiatives from a fabrication standpoint will be able to holistically evaluate these products in the light of ecological and health impacts, tailoring their application to the community's needs.

1.3 Thesis Structure

This thesis is organized as follows: First, a thorough literature review is carried out where studies about the recycling of mine tailings into construction materials were investigated to identify current areas of study with a focus on environmental, health, and social aspects. Both grey literature and peer-reviewed literature were considered. Then, environmental and health aspects in the recycling of mine tailings for construction purposes were integrated into a framework that suggests additional considerations for future projects in the mine tailings recycling into construction materials area (Chapter 2). Since this is an article-based thesis, Chapter 2 is a review paper in preparation for submission to the *Extractive Industries and Society* Journal. Expanding on the scope of this research, social aspects such as community perception, buy-in, and knowledge transfer (i.e., research translation) were further analyzed to provide tools and recommendations to researchers and academics when assessing the feasibility of these projects. These suggestions include descriptions of focus group activities and informational flyers that can be widely distributed among researchers, academics, and mining community members (Chapter 3). Chapter 4 comprises the overarching summary of this research and proposes ways forward for future researchers.

CHAPTER 2 – LITERATURE REVIEW

2.1 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 (LandLinks, n.d.), employing more than 100 million people (i.e., workers and families) worldwide and representing 93% of the overall mining workforce (The World Bank, 2013). In ASM operations, mine tailings, defined as the finely ground residue from the metallurgical processing of ore and are typically disposed of in the most convenient manner possible, oftentimes adjacent to populated areas or 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 & Hallberg, 2005). In gold production, mercury (Hg), and cyanide further complicate tailings management. Awareness of the health implications associated with the release of heavy metals by ASM operations are gaining awareness in many developing communities, spurring local level action among miners and communities towards formalization efforts (Veiga & Marshall, 2019). As part of such efforts, ASM operations have identified the critical need to initiate sustainable mine tailings management strategies (Veiga & Hinton, 2002). Mine tailing 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 & 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 tailing 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 & 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 grey literature 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 holistic approach some of the variables that should be accounted for in mine tailing 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 tailing 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.

2.2 Methodology

MTRAs are often conducted in developing countries by ASM miners 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. Therefore, this review combines both peer-reviewed and grey 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 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. Figure 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.

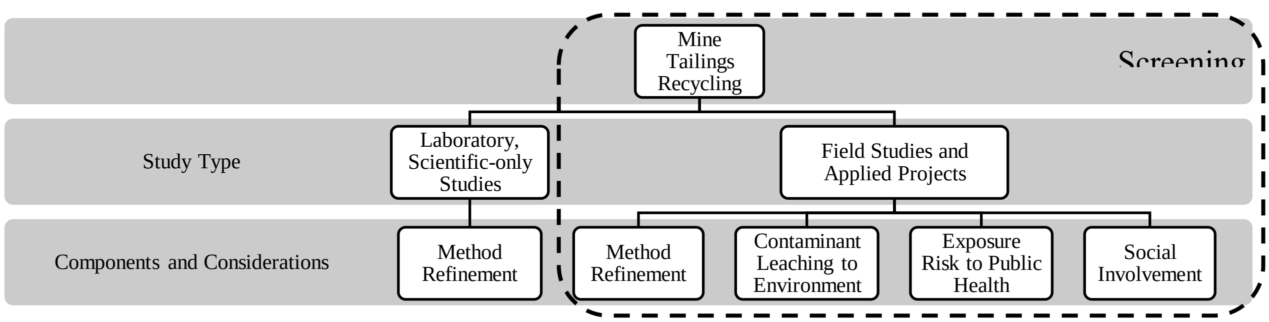

Figure 1: *Screening criteria (dotted box) used to select mine tailing recycling activities. The literature review was based on study type (lab or field), environmental, and health considerations.*

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 perspective, 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 from large-scale mining (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 1960-2021. 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 grey literature. For this work, the so-called grey literature is considered upon the basis of visible and verifiable information. For the grey literature, several web pages were used to find news, interviews, or related governmental information about mine tailing recycling strategies around the world. From Open Grey and WorldCat, the search strings used were [TITLE-ABS-KEY "tailings discipline:(08L - 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 grey literature accounting for three more studies. In total fifty-three studies around the world (see figure 2 for distribution) were considered for our literature review considering both grey 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" (MTRAs)*.

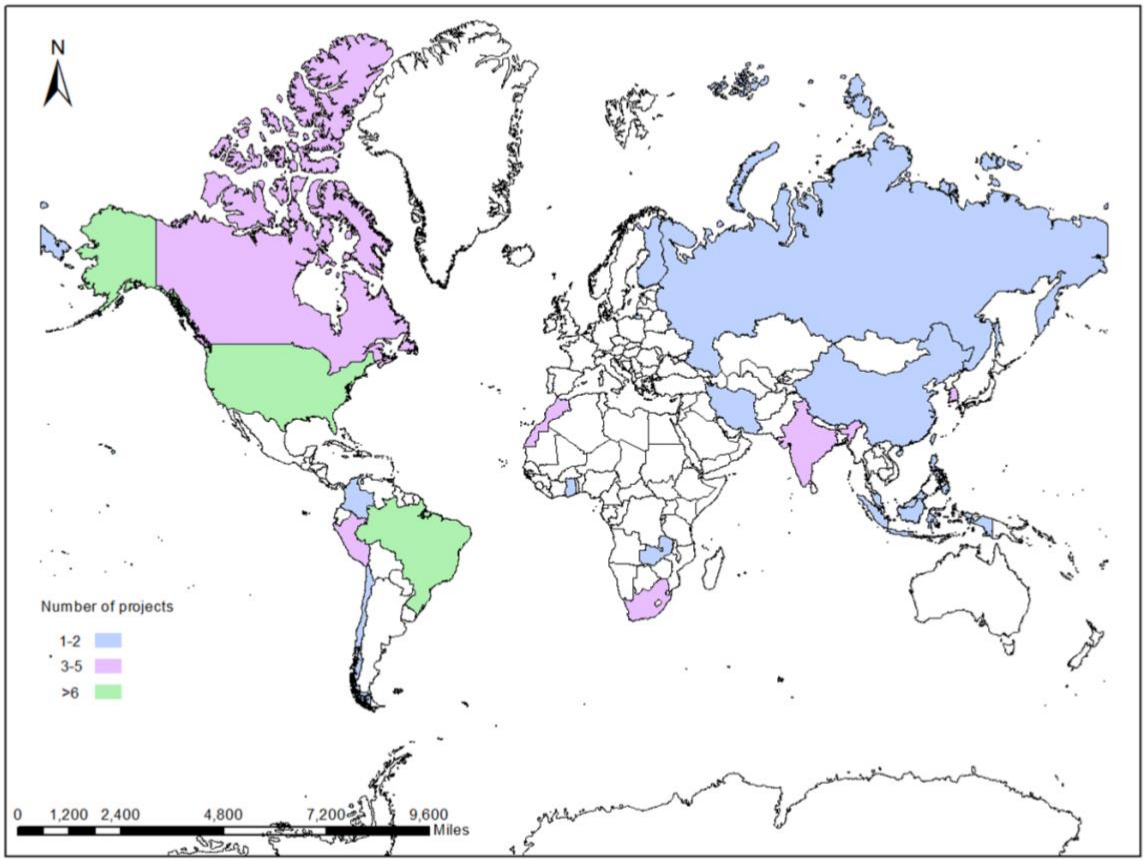

__Figure 2:__ Distribution of the analyzed Mine Tailings Recycling Activities (MTRAs) around the world.

2.3 Results

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

2.3.1 MTRAs processing and fabrication methods

The development of products such as bricks, mortars, or grout from mine tailing 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 tailing 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.

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

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 any 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.

2.3.2 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.

Table 2: *The material produced, and the 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

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 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.

2.3.3 Environmental and Health considerations 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).

2.3.3.1 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, el Adnani, et al., 2016) (Table 3).

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	10004,10005,10006,10007.	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.

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 some indication of the behavior of the mine tailing 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 tailing recycling process: (1) analysis of the mine tailings before any treatment or fabrication and (2) analysis of mine tailing 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, Benzaazoua, et al., 2016; Argane et al., 2015; Kiventerä et al., 2018; Mahmood & 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, Benzaazoua, et al., 2016; Argane, el Adnani, et al., 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 considered 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 tailing 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, el Adnani, 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 tailing 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.

2.3.3.2 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, respectively. 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.

2.3.4 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 literature. From a social perspective, community involvement is crucial for the development of activities and products, as stated by Ongley & Booty (1999), the knowledge-based approach can help use local knowledge to carry out important program objectives. Hence the incorporation if this additional social analysis.

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 tailing repurposing should focus on studies related to social welfare and suggests multidisciplinary approaches that involve technical and socio-economic 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 tailing 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

2.4 Discussion

2.4.1 Environmental and Health Considerations

Based on the scarcity of discussion regarding environmental, health, and social concerns associated with MTRAs, this section discusses the environmental considerations of using MTRAs in the community 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.

For the purpose of this discussion, we select examples of 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 holistically, 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 for community purposes. This framework is divided into two main categories: (1) Hazard Identification and (2) Exposure Assessment. A holistic approach to mine tailing 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.

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 the contamination 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.

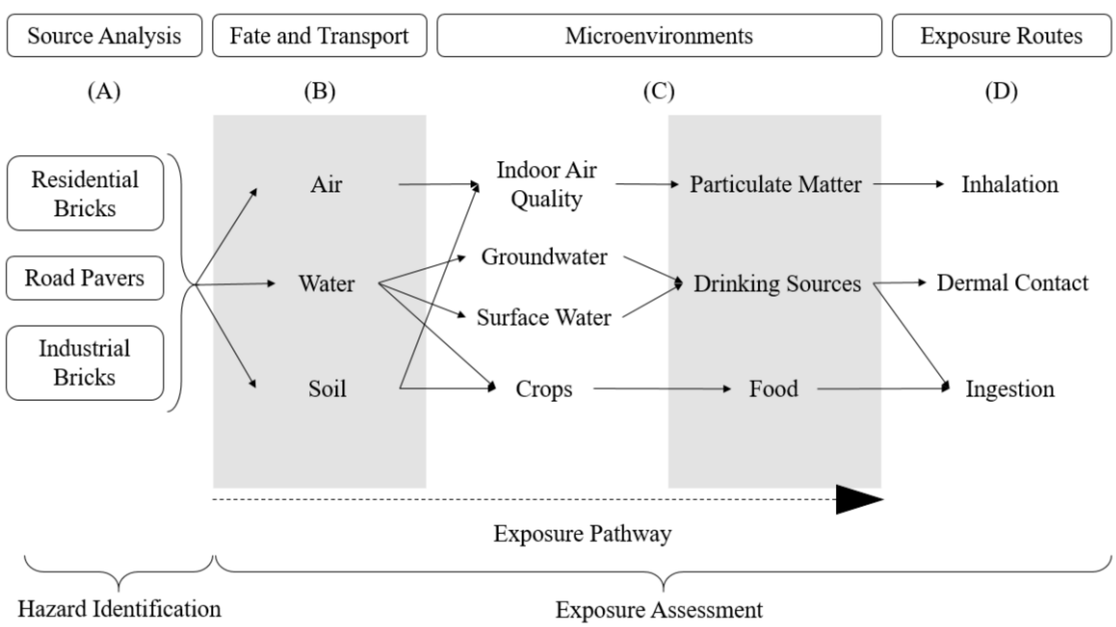

Figure 3: *Proposed Comprehensive Approach to Recycling Tailings (CART) framework for hazard identification and exposure assessment. Adapted from (National Academy Press, 1983; Watts, 1998; Maxwell, 2014).*

2.4.2 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 different 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 hazard, concepts like Concentration-Toxicity Screening (U.S. 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.

In the second step, Exposure Assessment, the transport of the previously identified heavy metals 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, contributing to the decision-making process of stakeholders.

2.4.3 Fate and Transport (B)

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, if not done properly in step one, 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.

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 & Koldas, 2006), have profound impacts in ecosystems and can severely contaminate soils, groundwater, and surface water (Peppas et al., 2000). To address this issue, most MTRAs have used test such as acid-base accounting (ABA), TCLP, and SPLP to determine acidic generation of materials (Bouzahzah et al., 2015). Such tests 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.

The importance of soils is directly related to mining operations and the health risk associated with 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 that when analyzing 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). Leaching tests for both solids and liquids can help in this section to properly characterize the recycled products to then be compared to the baseline in the hazard identification step.

The possibility to suspend small particles that can transport contaminants through the air is an important factor that has been neglected when developing MTRAs. 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 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). 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.

2.4.4 Microenvironments (C)

Potential hazards to public health and the environment are often analyzed using a risk assessment process with the goal of utilizing the assessment to provide a quantitative baseline for decision making. For example, a risk assessment can be used to determine the health effects resulting from a contaminant release such as air pollutants from an industrial facility or groundwater pollution from a landfill or, in this case, air, water, or soil pollution from heavy metal release from MTRAs. The EPA has detailed procedures in performing hazardous waste risk assessment (National Academy Press, 1983; U.S. EPA, 1989) that goes through the process of characterizing the contaminant at the source, evaluating the pathway that these contaminants may take to humans, plants, or animals and then assessing the toxicological effects on the receptor.

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 study shows 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, identifying where mine tailing 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 analysis since studies like this directly relate the possible environmental concerns and health risks associated with the exposure routes of contaminants for people using these mine tailing construction materials. Similarly, social aspects need to be considered to properly tailor the construction materials, their implications, and applications for communities seeking to use the recycling alternative.

2.4.5 Exposure Routes (D)

When analyzing environmental impacts and risks associated with MTRAs, human health is prioritized since the health implications of mine tailing 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 tailing 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 (B) in the CART framework are key for people's subsistence in these developing 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); 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.

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 (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).

2.4.6 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 transition 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 and the relationship between economic benefits and the health of people willing to use these materials.
- Understanding social contexts
    - Economic cost associated with the fabrication, making it feasible for communities to implement.
    - The mass production of materials, and possibilities of communities to produce these materials on their own.

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

2.5 Conclusions

As the popularity of mine tailings recycling (MTR) continues to gain traction worldwide in ASM, there is a critical need to understand the environmental, health, and social risks associated with its reuse to maintain the health and quality of life for developing communities. This review synthesized information from 53 mine tailing recycling projects worldwide, both from academic and grey literature.

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 community construction, potential hazards to public health and the environment require consideration. 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 developing communities, 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.

Further focus on the social implications of such activities is warranted and requires further analysis and attention in field application.

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CHAPTER 3 – KNOWLEDGE TRANSFER

The sustainable development of community-based projects requires the consideration of aspects such as community's desires and needs, stakeholder involvement, and long-term effects. These aspects should be taken into account to better help communities understand the contributions of engineers in different technical aspects that may improve communities' way of life, as well as to help engineers better understand the communities that they are serving (Parsons, 1996). Therefore, consideration of social aspects is directed towards the knowledge transfer in communities where the recycling of mine tailings may take place. As demonstrated by O'Brien et al. (2020) most projects in developing communities fail to incorporate initial stakeholder analysis, giving little to no details to communities on how to properly assist in efforts that can benefit the design of solutions from engineers and their application in the intended community. Resulting in project delays, failure, or total disconnect with the reality of people in the community. Hence, the importance in the implementation of knowledge-based (K-B) approaches that incorporate local domain knowledge into the development of projects (Ongley & Booty, 1999).

To consider these knowledge-based approaches into the design of solutions that not only considers community's needs but also incorporates these needs into the design of alternatives, several activities and approaches have been studied, these include discussions, debates, conferences, seminars, and workshops. The latter being the most used in adult education as identified by the literature (Chambers, 2012; Mauser et al., 2013; Tate, 2009). However, the development of workshops in which the presenter is the only speaker is not recommended since it does not create the collaborative and cooperative environment required for a successful workshop (Tate, 2009), where participants can share their ideas and create meaningful experiences from these workshops. Furthermore, to address this collaborative/cooperative environment concepts have been studied that have helped shape the education and transfer of knowledge, such as the concept of transdisciplinary research, which is defined as efforts conducted by researchers from several disciplines working together to advance knowledge, integrating discipline-specific approaches to solve common problems (Aboelela et al., 2007). Such concepts can represent viable solutions in the integration of academic and non-academic participants into the design process of the workshops, ultimately fostering future environmental sustainability (Mauser et al., 2013). Combining workshops and transdisciplinary approaches may help addressing the knowledge transfer in the recycling of mine tailings process.

As identified in chapter 2, the social approach to MTRAs has not been fully investigated nor considered within the projects themselves, leaving several aspects such as community engagement, risk perception, and knowledge transfer from people developing MTRAs to communities, outside of the scope of the projects. Therefore, chapter 3 will discuss activities that help stakeholders (e.g., academics, mining community members, researchers, and NGOs) better understand recycling activities. These activities encompass the transfer of the acquired knowledge to communities and miners by developing a workshop that helps understand their need while at the same time learn about the required processes in the assessment and evaluation of possible health and environmental implications of the mine tailing recycling process. These activities also seek to serve community members, miners, academics, and organizations developing recycling strategies by understanding and co-creating community-based applications of MTRAs, illustrating the importance of recycling mine tailings while providing considerations needed to develop better recycling practices. Similarly, stakeholder engagement and perceptions related to the use of these materials in construction projects are included in these activities. Also, these activities are to be developed and carried out by governmental organizations, NGOs, or community members looking for better ways to assess the development of recycling activities or looking to involve communities in the recycling process.

3.1 Communicating Science to ASM communities

In social and scientific literature, there are two concepts that help understand the knowledge transfer from different perspectives, research translation and science communication. Research translation is a concept that has been widely used in health sciences, it refers to "…translating research into practice, ie (sic), ensuring that new treatments and research knowledge actually reach the patients or populations for whom they are intended and are implemented correctly" (Woolf, 2008). Although this definition is medical it can be adapted to MTRAs giving a working definition for this thesis as: "The process of generating knowledge that can be applied and implemented correctly in the communities that MTRAs seek to serve". This differs from scientific communication as it goes beyond basic explanation of a scientific phenomenon and seeks to actively apply the scientific principles into meaningful community engagement. Studies developed in the area, give details in what type of information is more relevant to different populations within a community and can disseminate easier and faster, allowing researchers better frame their findings and communication efforts to create bigger impacts (Milkman & Berger, 2014).

On the other hand, scientific communication to communities is defined as: "the exchange of information and viewpoints about science to achieve a goal or objective such as fostering greater understanding of science and scientific methods or gaining greater insight into diverse public views and concerns about the science related to a contentious issue" (National Academies of Sciences, Engineering, 2017). However, when incorporating this definition to controversial topics such as using mine tailings as raw material for the fabrication of construction products, several challenges need to be incorporated into the analysis. These challenges include conflicts between beliefs and values, communities' uncertainty due to contradictory messages between communicators, and the amplification of speech of influential individuals that can block clear communication of scientific evidence (National Academies of Sciences, Engineering, 2017).

In this chapter, both scientific communication and research translation are going to be studied incorporating the findings of Milkman & Berger (2014) to properly tailor the scientific knowledge to better reach the different audiences in ASM communities. The objective of this chapter is to give the necessary tools to properly transfer to communities the required knowledge to improve and assess recycling practices from a community engagement perspective. These recycling practices have the ability to further damage the environment and people's health by utilizing heavy metal-laden tailings into construction materials for community purposes. Although there are promising results encapsulating contaminants, efforts in the identification of environmental and health implications of this activity are not well understood by communities nor people carrying out this activity, posing a huge risk for contaminant mobilization to the environment and additional heavy metal exposure pathways to people living around these construction products. Hence, efforts in the knowledge transfer topic are required and imperative for successful and sustainable development of recycling projects in communities, helping stakeholders in the decision-making process, by facilitating tools that create awareness so that people can make informed decisions.

In order to address aforementioned issues, needs, and objectives a workshop that utilizes the concepts of research translation and science communication is proposed. This workshop will incorporate communities' needs into the design process to properly assess the development of new projects. Also, this workshop will give insights into the community's thinking process, and the feasibility in the real use and applications of these construction materials within the same community. This workshop is thought to be developed following the flowchart in figure 4.

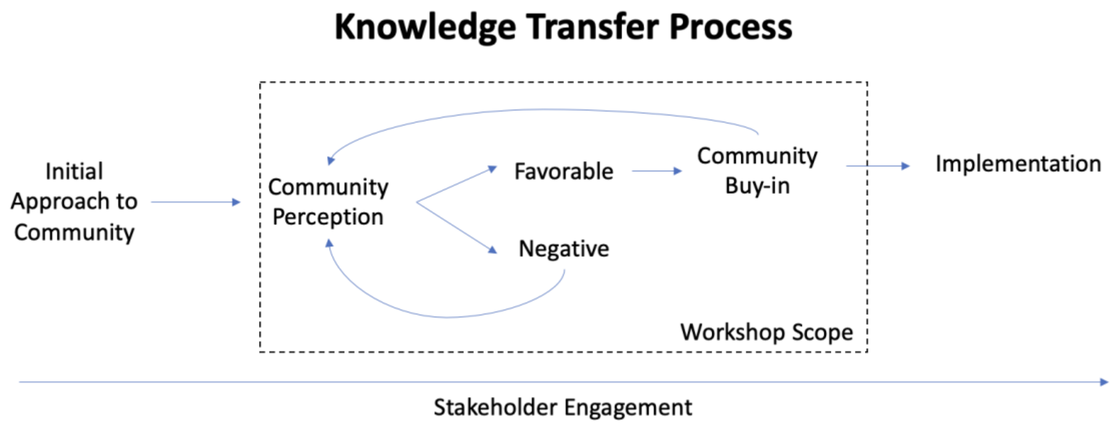

Figure 4: *Scheme of the knowledge transfer process in the proposed workshop. The workshop aims to assess and cover the dotted line by incorporating the community's perception as a fundamental aspect in the development of the activity.*

In this process community perception is a key element in the analysis of these recycling initiatives. Negative perception of community members will lead to gain better insights of the concerns of the community that can then be considered in the process. Also, community buy-in is key since most of the applications reviewed in chapter two are intended to serve community purposes. In this way, the workshops aims to address long term concerns and stablish common grounds so that the decision making process of communities is incorporated into the translation of knowledge.

3.2 Community Workshop in ASM

To address science communication issues such as conflicts between values and beliefs, community perception, and buy in processes, community members that are not part of the development of MTRAs are also involved in the knowledge transfer process since the identification of risk perception is directly related to the social aspects as well. This is the first step in the knowledge transfer process and tries to incorporate the risk that people think they may be exposed to when using these mine tailing-based construction materials. This will allow for a better understanding of community buy-in and future commercialization of MTRAs.

In table 4, the aspects that should be considered in this step are shown. This activity is divided into three main activities, the introduction of recycling mine tailings to stakeholder that are not familiar with these initiatives, the assessment of the stakeholder’s perception regarding these previously introduced new concepts, and the environmental and health implications in the use of mine tailings for construction purposes. The latter being a brief overview of key aspects to consider when assessing the feasibility of recycling projects in the community. It is important to mention that as described in table 4, participants in this initial step will be community members, government officials, and any other stakeholder that may be involved in the supply chain of the construction products.

Table 4: *Initial step required to understand stakeholder engagement - Development of risk perception of community stakeholders*

Risk perception of community stakeholders	
Objective	The objective of this pre-workshop with community members is to understand and identify the perception of different stakeholders in the community, namely in the recycling of mine tailings for construction purposes. Understanding risk perception of community stakeholders and assessment of needs.
Reach	To understand the perception that people may have regarding the use of mine tailing-based construction materials and how the concept of MTRAs would adapt within the community.
Participants	Community members, government officials.
Activities	**Initial concepts assessment:** For monitoring and evaluation purposes, questions regarding initial concepts of construction materials and mine tailings are asked to participants to determine the level of understanding they have about the topics that are going to be discussed later in the workshop.
	Mine tailings recycling into construction materials: The introduction to MTRAs topic is presented. Attendees learn about mine tailings and their potential utilization in construction projects.
	Community perception*: In groups, participants discuss their first thoughts about the idea of using mine tailing-based construction products and possible applications from their particular experiences and desires.
	Environmental and health implications: Under an exposure assessment perspective, concepts are presented to attendees explaining the advantages and disadvantages of the recycling of mine tailings. Also, considerations are given on how to properly assess new projects that may be developed in the future, things to test for, and different analyses that can be done to deem products safe.
	Final concepts assessment: Learning outcomes are evaluated in the light of participant's perception of new concepts, as well as the perception of the products after understanding the environmental and public health considerations.

* Activities required to understand social context, can be done in small groups.

This risk perception is then analyzed to determine the viability of developing these recycling activities in the region, accounting for people’s concerns and specific requests that in the previous stage were identified. The outcome of this stage can have several implications for the recycling process in the community, these include the favorable or negative perception of people, possible concerns, and advantages or disadvantages that the community may perceive. This is evidenced in large scale mining (LSM) initiatives (Anglogold Ashanti, 2020) where efforts in the development of construction materials with social impact have been largely researched and developed under circular economy policies, adding sustainability to their operations. However, efforts in community engagement and people's acceptance fall short.

After the analysis of the information gathered in the community perception step, key aspects, concerns, or disadvantages that the community perceived are then used to shape the workshop, to properly incorporate into the co-designed activities, solutions to important aspects such as community buy-in.

This workshop consists of a three-day meeting where processing plant owners and miners already working in MTRAs or wanting to learn more about this activity, will discuss and implement useful tools for the development of strategies that will help them understand and create unique ideas based on their cultural experience, background, and knowledge of the community. Although this workshop was initially thought to be in-person, due to current worldwide circumstances (i.e., COVID 19 Pandemic) it can be developed virtually. Initial two days are part of the co-design efforts to determine and identify specific community needs and key community strengths that can be used to develop these recycling initiatives based on their particular needs and community set up. Similarly, these initial two days will introduce participants to key concepts of recycling and environmental importance of mine tailing disposal, the attendees themselves will be in charge of understanding the environmental importance of recycling and proper disposal of mine tailings through collaborative group efforts.

The third day is focused on the three main aspects of mine tailing recycling, technical fabrication methods, environmental testing protocols to properly assess environmental concerns, and health related issues associated to possible heavy metal exposure pathways. In this day, recommendations on how to assess and test these construction materials from an environmental standpoint are provided, as well as some recommendations to reduce the mobility and exposure of contaminants from a health perspective. Figure 5 summarizes the main aspects, objectives, actions, and outcomes of these three main aspects as well as the current section of knowledge transfer as a general overview of the recycling activities.

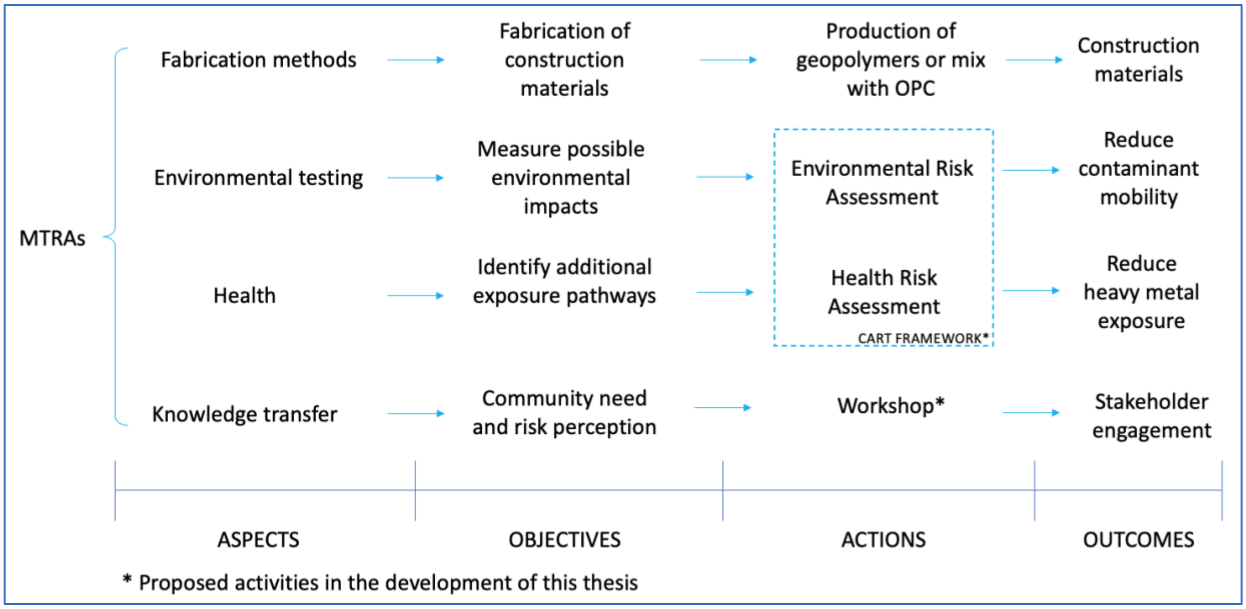

Figure 5: *Overview of considered aspects of Mine Tailing Recycling Activities (MTRAs)*

Additionally, to give workshop participants a visual representation of what the process of recycling mine tailings looks like, a brochure is proposed detailing the key aspects that should be considered for a more comprehensive study in the development of recycling projects. In an effort to include communities in Latin America the trifold brochure is presented in both English and Spanish, appendix A and B, respectively. It contains graphics that help convey the idea of the steps required for a better understanding of mine tailings recycling. This brochure shows the three most important aspects identified in chapter 2, as well as the different steps in the recycling process, and a graphic representation of the CART framework. Also, contact information of people in charge of the initiatives locally and the link to the central website *SEN Colectivo Educativo* where all the material for the workshop can be found, will be provided.

The information that will be shared in the development of the workshop is listed in the next subsections:

3.2.1 Fabrication Methods

The development of products from mine tailing recycling involves a series of processes and fabrication methods to produce a final material. These processes can incorporate innovative technologies and can ultimately produce different final products. From chapter two, we could determine two main recycling processing methods, the mixture of Ordinary Portland Cement (OPC) with mine tailings for the production of concrete-based materials and alkaline activation (geopolymerization).

Alkali-activation is a chemical process that mixes an aluminosilicate compound with an alkaline activator to produce a material that is resistant to corrosion and readily develops compressive strength (Palomo & Jimenez, 2011). For example, geopolymerization is an alkali-activation technique that has been widely studied in the mine tailings recycling processes (Ahmari & Zhang, 2012; Aseniero et al., 2019; Chen et al., 2012; Comrie et al., 1988; Jaarsveld et al., 2000; Kiventerä et al., 2016; Komnitsas & Zaharaki, 2007). Geopolymerization ultimately results in materials with ceramic-like properties, low shrinkage, and freeze-thaw resistance (Davidovits et al., 1990). However, the ratios between Al/Si and the balance of mixture composition are oftentimes hard to achieve to meet key parameters in the fabrication of geopolymers, adding complexity to the overall production (Majidi, 2009).

The mixture of mine tailings with OPC is a method that has been largely studied, showing promising results in both mechanical properties and chemical encapsulation (Argane et al., 2015, 2016; Benarchid et al., 2019; Lv et al., 2019; Mahmood & Elektorowicz, 2020), serving as a starting point for communities trying to develop these kinds of strategies. Nevertheless, the contribution to the carbon footprint is considerably high compared to that of the geopolymers.

3.2.2 Environmental Testing

In this section material design for the workshop regarding environmental testing is shown.

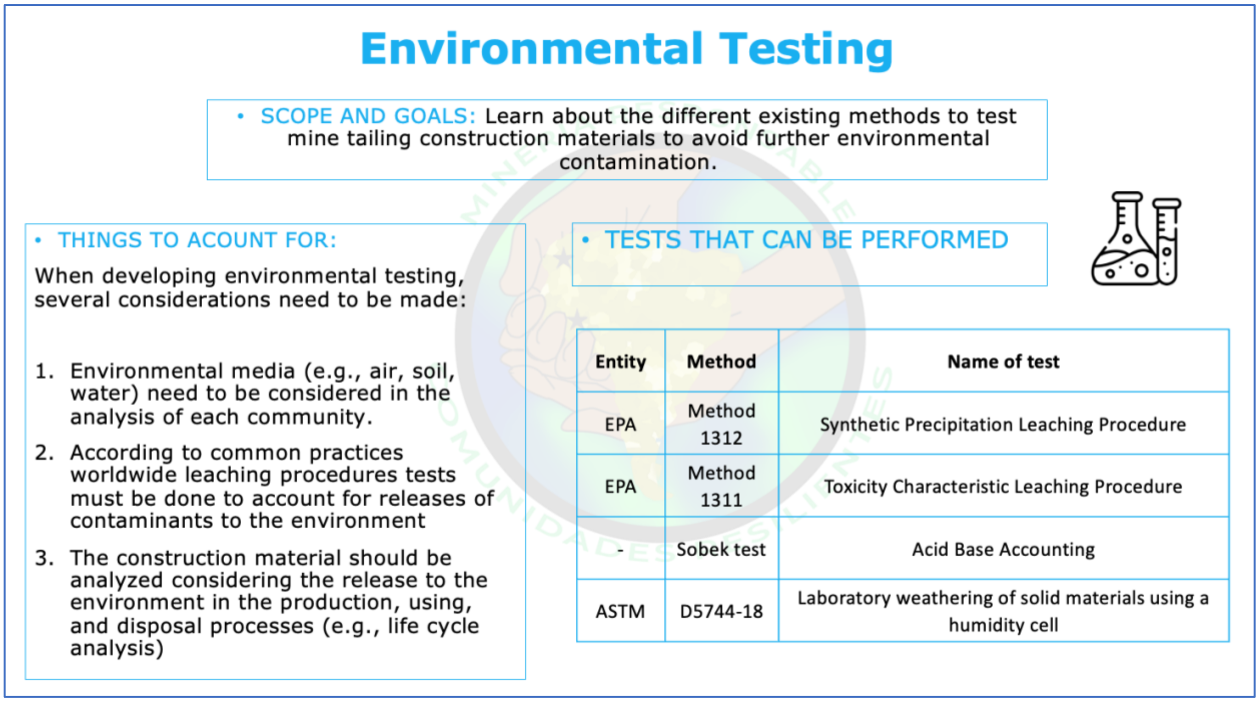

Figure 6: *Environmental testing material for the workshop. Considerations and environmental tests that can be performed*

3.2.3 Health Considerations

Material design for the health section is presented. This material consists of two pages, where relevant information regarding the considerations and examples are presented. Also, public health terms are introduced to give general understanding of the factor influencing the process.

Several ways have been studied to address the indoor air quality assessment, and as proposed in chapter two, alternative studies such as the simulation tool kit for indoor air quality and inhalation exposure (IAQX) can serve as an early approach to identifying estimate of exposure.

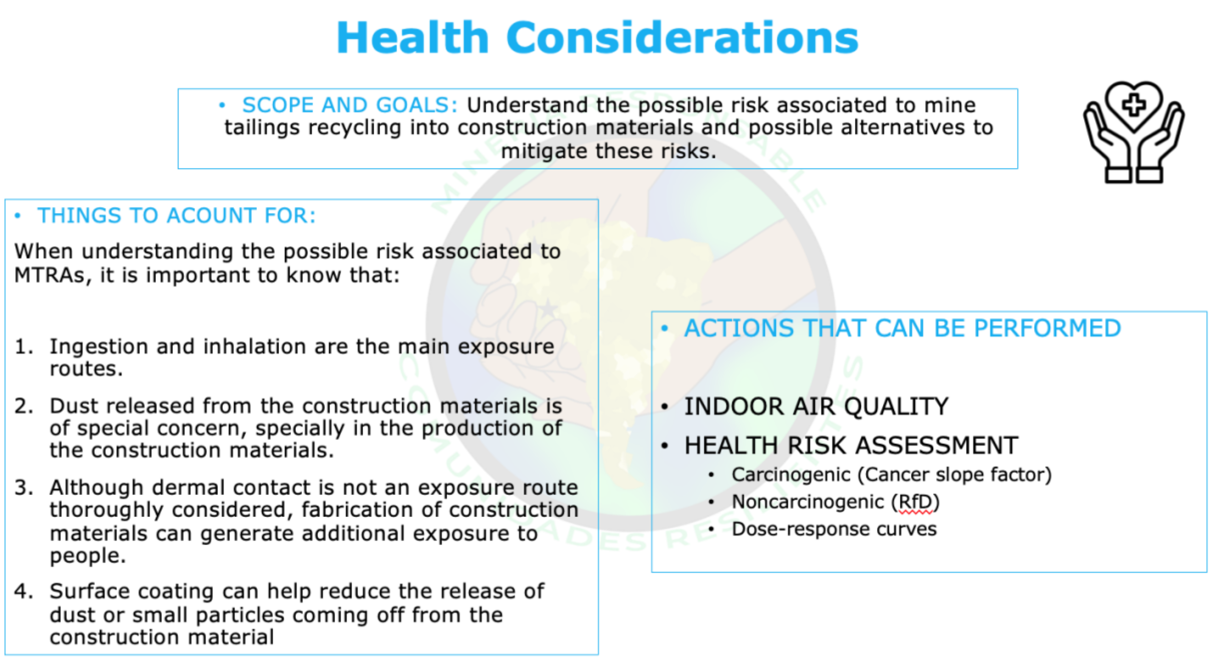

Figure 7: *Health considerations material for the workshop. General information regarding the health aspects of MTRAs and actions that can be taken*

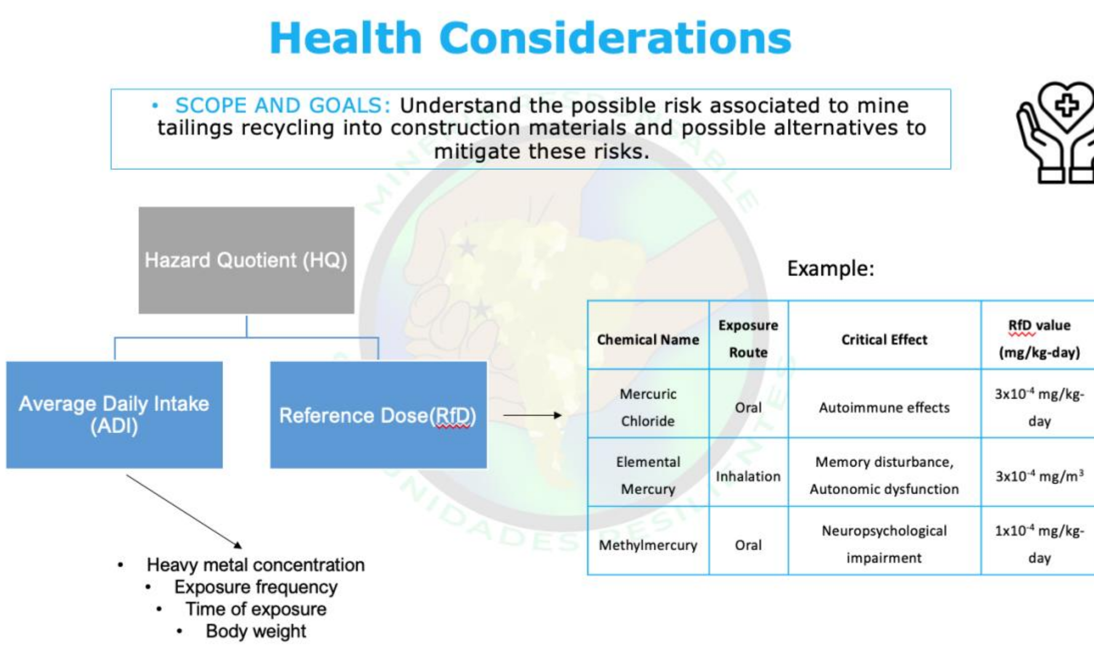

Figure 8: *An example of the reference dose for mercury is presented as a way to determine the risk associated with the ingestion and inhalation of this chemical and its forms.*

Table 5: Workshop 1 – Recycling of mine tailings for people involved in the production of MTRAs

Workshop 1 – Understanding recycling, processing, and alternatives in mine waste disposal for construction purposes.			
Objective	The objective of this workshop is to introduce miners and processing plant owners to the recycling of mine tailings, understanding their needs, experiences, and limitations, to provide useful tools and knowledge that will help them identify opportunities in the development of the recycling of mine tailings (MTRAs).		
Reach	To let stakeholders involved in the recycling of mine tailings know about possible ways to address the recycling of mine tailings from a holistic approach.		
Outcome	With this workshop participants are expected to learn and understand better practices in the recycling of mine tailings, from the technical fabrication methods to the environmental testing used, as well as actions used to reduce heavy metal exposure.		
Participants	Miners, processing plant owners, people interested in developing MTRAs.		
	Day 1 - Introduction to Recycling	**Day 2 - Mining activity and tailings**	**Day 3 - Mine tailing recycling**
Activities	**Presentation of the group:** This first stage helps acquaint participants of the workshop with facilitator and people in charge of instructing the material.	**Mining activity*:** Here attendees discuss the particularities of their operations, an important consideration is given to the mineral processing operation and limitations they may have. This enables proper interpretation of issues and the cocreation of possible solutions to those limitations.	**The intersection of mine tailings and recycling:** The process of recycling mine tailings for construction purposes is introduced and discussed based on previous days interactions and acquired knowledge.
	Introduction: Here the objectives and outcomes are stated, giving attendees the required tools to properly develop the workshop.	**Supply chain mapping*:** This is an important step to understand the commercialization process and the different steps required to take the ore from the mine to the final disposal of mine tailings.	**Social Initiatives*:** Participants are asked to elaborate on current initiatives that have been developing regarding the final disposal of mine tailings, identifying current projects, and the willingness of processing plant owners to initiate this recycling approach.
	Icebreaker activity	**Mine tailings identification activity*:** Through a survey, attendees are asked about their knowledge of mine tailings, the contaminants tailings may have, the fate and transport of these contaminants, and their impacts on ecosystems.	**E&H Implications:** Here, the environmental and health considerations of this work are presented to participants to help them understand the possible implications and aspects that they should account for when developing MTRAs.
	Initial concepts assessment: For monitoring and evaluation purposes, questions regarding initial concepts such as recycling, mine tailings, and construction materials are delivered to understand the state of the knowledge among the participants.	**Mine tailing environmental and health considerations:** Based on the general knowledge acquired from the previous step, attendees are introduced to the real impacts of mine tailings to the environment and public health, possible mitigation, and ways forward.	**Final concepts assessment:** Learning outcomes are evaluated in the light of participant's perception of new concepts, as well as the ability for using the knowledge to start thinking in better alternatives that help in the sustainability of their operation.
	Recycling*: The concept of recycling is introduced. General perspectives and local initiatives are discussed to address from a holistic perspective the understanding of the recycling concepts of the attendees.		**Conclusions**

* Activities required to understand social context. Can be done in small groups.

CHAPTER 4 – CONCLUSIONS AND FUTURE RESEARCH

Worldwide development in the recycling of mine tailings has mostly focused on the study of technical and scientific concepts that improve mechanical properties of construction materials, though not fully understanding the implications of their works within communities. From the literature review, several analytical tests are determined to be used more often by academics, researchers, and community members that are studying the recycling of mine tailings, but these analytical tests do not necessarily represent all environmental implications and are solely done to determine the leachability of heavy metals out of the fabricated construction products. Similarly, health effects were only analyzed by NGOs when trying to understand the impacts of people already living in communities where the use of mine tailings as raw material for bricks was extensively done without the required environmental and health analyses. Following this, social aspects of the recycling initiatives are completely overlooked, leaving aside the applications, communities' perception, stakeholder engagement, and scientific communication from researchers to communities where such projects may take place.

To address the environmental testing and health considerations, a framework is proposed that holistically looks at these aspects from a risk assessment perspective, providing community members, researchers, and NGOs with an additional tool to develop a more comprehensive evaluation of the projects that are being studied or implemented in specific sites. The CART framework analyzes the hazard identification of mine tailings, prior to its incorporation in the recycling process, by testing heavy metal concentration and physical characteristics of mine tailings, helping create a baseline that will help later in the exposure assessment analysis. Then, the three environmental media are analyzed, air, water, and soil using different tests and analytical techniques to determine the concentrations of the fabricated products to then study the pathways in which the contaminants may travel. Lastly, the levels of intake are also analyzed using public health methods to determine the real risk associated with the use of mine tailings in construction materials. Although investigated MTRAs show promising results constraining contaminants, studies including the CART framework can help communities and researchers develop more sustainable practices that will increase favorable community perception.

Community perception and stakeholder engagement activities are presented to address the transfer of knowledge, helping communities make informed decisions regarding the use of mine tailings in construction applications. Activities such as workshops, presentations, and interviews with stakeholders may elucidate opportunities for improvement and social development.

From a technical standpoint, further research in the development of stronger and more eco-friendly methods to produce constructions materials is proposed. Technologies like geopolymerization and the use of activators different than fly ash may help reduce emissions of CO2 to the atmosphere compared to the use of OPC to mix with mine tailings. From an environmental perspective, the use of alternative tests to analyze from different scenarios, leaching and particulate matter release rates, will be important to analyze prior to implementation of construction materials in communities. Also, future research includes the application of the CART framework, analyzing case studies where all variables are considered and aiming to understand the life cycle of the construction materials and the exposure that individuals will be subjected to. Similarly, the development of workshops and fluent communication with communities is encouraged in order to maintain a flow of communication and feedback with community members.

Overall, this research provides more information regarding the analysis of mine tailings recycling for construction purposes, elaborating in the environmental, health, and social considerations required to better assess and implement projects that can increase sustainability efforts in mining communities. Efforts in this topic require an immense commitment of researchers and academics of different disciplines to give meaningful solutions and long-lasting results.

Findings from this research will contribute to better assess mine tailing recycling activities from an ecological and public health perspective. Avoiding further damage to the environment and potential exposure pathways associated with heavy metal contamination. Researchers, academics, and people seeking to pursuit these recycling activities may find interesting avenues to socialize these projects. Activities such as workshops help engage communities and stakeholders from more comprehensive approaches that allow recycling initiatives owners to give technical and scientific credibility, as well as community buy in to these mine tailing recycled products. It will also contribute to the advancement of the communication between scientific community and society to better tailor future initiatives to communities needs and desires.

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APPENDIX A – BROCHURE

MINE TAILING RECYCLING

Info to improve recycling initiatives

Responsible Mining Resilient Communities

More info:

SEN Colectivo Educativo

https://rmrc-research.uta.edu/

The University of Texas at Arlington

Artisanal and Small-Scale Mining (ASM) has little to no regulations pertaining to mine tailings management and final disposal.

Mine tailings represent the main source of heavy metal contamination of polymetallic mining[1].

Environmental and health concerns are linked to the improper disposal of mine tailings[2].

In order to properly address these issues, several aspects should be considered.

THREE IMPORTANT ASPECTS

1. ENVIRONMENT

Mobility of heavy metals through the environment is one of the concerns when developing recycling initiatives.

2. HEALTH

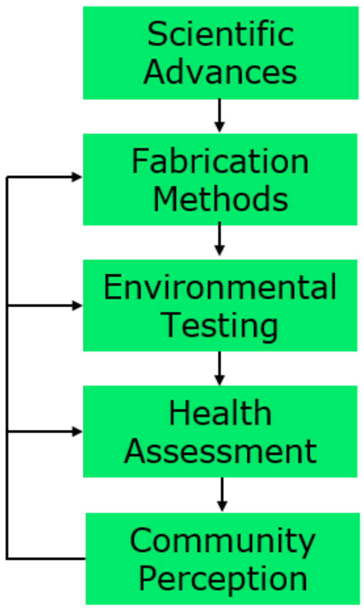
According to the intended purpose, it is important to assess the health of people utilizing final construction products.

3. SOCIAL

Cultural evaluation of risk and importance of stakeholder engagement in the perception of these newly developed products.

PAGE 1

STEPS IN THE RECYCLING PROCESS



Scientific Advances
Development of new technology to incorporate in the recycling process.

Fabrication Methods
Different techniques used to fabricate the construction materials (e.g., geopolymers).

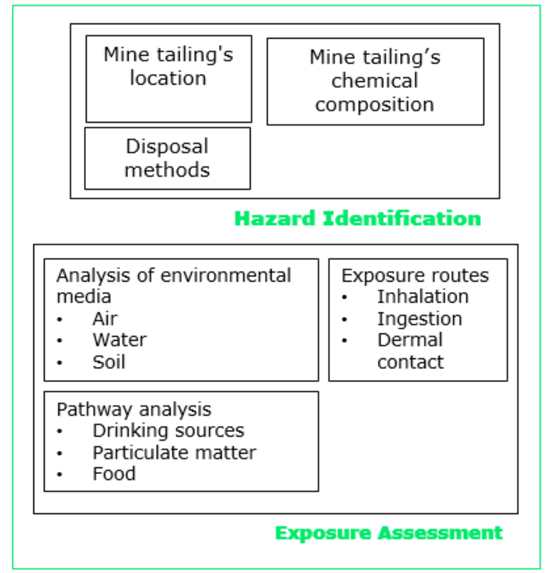
Environmental Testing
Mobility testing to determine leaching behavior of contaminants (i.e., heavy metals).

Health Assessment
Possible health effects of using construction materials.

Community Engagement
Stakeholder engagement to determine risk perception and community's buy-in process.

COMPREHENSIVE APPROACH TO RECYCLING TAILINGS

Created to help assess the aspects of recycling from a risk assessment standpoint.



Risk Assessment

APPENDIX B – BROCHURE (SPANISH)

RECICLAJE DE COLAS EN MINERÍA

Información para el mejoramiento de las iniciativas de reciclaje.

Comunidades Resilientes de Minería Responsable

Mas información:

SEN Colectivo Educativo

https://rmrc-research.uta.edu/

Universidad de Texas en Arlington

La minería artesanal y de pequeña escala (MAPE) tiene poca o ninguna regulación relacionada con el manejo y disposición final de colas (o relaves) mineros.

Las colas mineras representan la principal fuente de contaminación por metales pesados en minería polimetálica [1].

Las preocupaciones ambientales y de salud pública están relacionadas con la disposición inadecuada de relaves mineros [2].

Para abordar adecuadamente estos problemas, se deben considerar algunos aspectos, principalmente los descritos a continuación.

ASPECTOS IMPORTANTES

1. MEDIO AMBIENTE

El transporte de los metales pesados a través del medio ambiente es una de las preocupaciones a la hora de desarrollar iniciativas de reciclaje.

2. SALUD

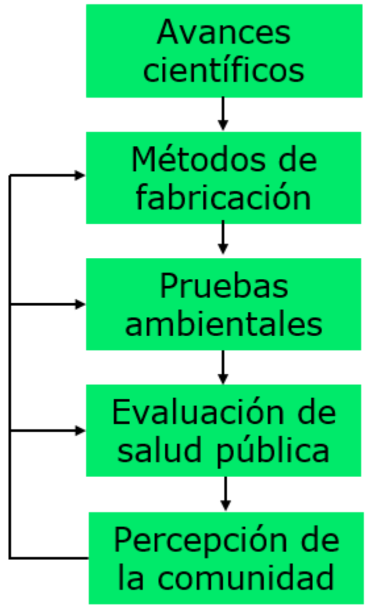
De acuerdo con el propósito planteado, es importante evaluar la salud de las personas que utilizan los productos finales (productos de construcción).

3. SOCIAL

Evaluación cultural del riesgo, y la importancia de la participación de las partes interesadas en la percepción de estos productos recientemente desarrollados.

PAGE 1

PASOS EN EL PROCESO DE RECICLAJE



Avances científicos
Desarrollo de nueva tecnología para incorporar en el proceso de reciclaje.

Métodos de fabricación
Diferentes técnicas utilizadas para fabricar los materiales de construcción. Por ejemplo, geopolímeros.

Pruebas ambientales
Pruebas de movilidad para determinar el comportamiento de lixiviación de contaminantes (es decir, metales pesados).

Evaluación de salud pública
Posibles efectos en la salud del uso de materiales de construcción.

Percepción de la comunidad
Participación de las partes interesadas para determinar la percepción del riesgo y el proceso de aceptación de la comunidad.

ENFOQUE INTEGRAL PARA EL RECICLAJE DE COLAS

Creado para ayudar a evaluar los aspectos del reciclaje desde la evaluación de riesgos.

Evaluacion de Riesgo

APPENDIX C – WORKSHOP 1 (SPANISH)

Taller 1 – Comprendiendo el reciclaje, el procesamiento y las alternativas en la eliminación de desechos mineros en materiales de construcción.			
Objetivo	El objetivo de este taller es presentar, a los mineros y propietarios de plantas de procesamiento, el concepto de reciclaje de relaves mineros, entendiendo sus necesidades, experiencias y limitaciones, para brindarles herramientas y conocimientos útiles que les ayuden a identificar oportunidades en el desarrollo del reciclaje de relaves mineros. (MTRAs).		
Alcance	Informar a las partes interesadas involucradas en el reciclaje de relaves mineros sobre posibles formas de abordar el reciclaje de relaves mineros desde un enfoque holístico.		
Participantes	Mineros, propietarios de plantas de procesamiento, personas interesadas en desarrollar MTRAs.		
	Dia 1 – Introducción al reciclaje	**Dia 2 - Actividad minera y relaves**	**Dia 3 – Reciclaje de relaves de minería**
Actividades	**Presentación del grupo de trabajo:** Esta primera etapa ayuda a presentarse y a generar confianza entre los participantes del taller y los facilitadores encargados de desarrollar el taller.	**Actividad minera*:** Aquí los asistentes discuten las particularidades de sus operaciones, se le da una consideración importante a la operación de procesamiento de minerales y las limitaciones que puedan tener. Esto permite una interpretación adecuada de los problemas y la creación conjunta de posibles soluciones a esas limitaciones.	**La intersección de los relaves de la mina y el reciclaje:** El proceso de reciclaje de los relaves de las minas para fines de construcción se presenta y discuten en base a las interacciones de los días anteriores y al conocimiento adquirido.
	Introducción: Aquí los objetivos del taller son presentados, dando a los asistentes las herramientas necesarias para desarrollar adecuadamente el taller.	**Mapeo de la cadena de suministro*:** Este es un paso importante para comprender el proceso de comercialización y los diferentes pasos necesarios para llevar el mineral desde la mina hasta la disposición final de los relaves.	**Iniciativas sociales*:** Se solicita a los participantes que expliquen las iniciativas actuales que se han estado desarrollando con respecto a la disposición final de los relaves de la mina, identificando los proyectos actuales y la voluntad de los propietarios de las plantas de procesamiento para iniciar este enfoque de reciclaje.
	Rompehielos	**Actividad de identificación de relaves mineros*:** A través de una encuesta, se pregunta a los asistentes sobre su conocimiento sobre los relaves mineros, los contaminantes que pueden tener, el destino y transporte de estos contaminantes y sus impactos en los ecosistemas.	**Implicaciones ambientales y de salud:** Aquí, las consideraciones ambientales y de salud de este trabajo se presentan a los participantes para ayudarlos a comprender las posibles implicaciones y aspectos que deben tener en cuenta al desarrollar las MTRAs.
	Evaluación de conceptos iniciales: Para propósitos de monitoreo y evaluación, se entregan preguntas sobre conceptos iniciales como reciclaje, relaves de minas y materiales de construcción para comprender el conocimiento previo de los participantes.	**Consideraciones ambientales y de salud de los relaves mineros:** con base en el conocimiento general adquirido en el paso anterior, se presenta a los asistentes los impactos reales de los relaves mineros en el medio ambiente y la salud pública, la posible mitigación y los caminos a seguir.	**Evaluación de conceptos finales:** Los resultados de aprendizaje se evalúan a la luz de la percepción de los nuevos conceptos por parte de los participantes, así como la capacidad de utilizar los conocimientos para comenzar a pensar en mejores alternativas que ayuden a la sustentabilidad de su operación.
	Reciclaje*: Se introduce el concepto de reciclaje. Se discuten perspectivas generales e iniciativas locales para abordar desde una perspectiva holística la comprensión de los conceptos de reciclaje de los asistentes.		**Conclusiones**

* Actividades necesarias para comprender el contexto social. Se puede realizar en grupos.

APPENDIX D – STEP 1 OF WORKSHOP (SPANISH)

Percepción del riesgo de los actores de la comunidad	
Objetivo	El objetivo de este taller es comprender e identificar la percepción de los diferentes actores de la comunidad, principalmente en el reciclaje de relaves mineros para construcción. Además, se presenta a los participantes conceptos de evaluación de riesgos para que comprendan aspectos relacionados con el uso de materiales de construcción.
Alcance	Comprender la percepción que la gente puede tener sobre el uso de materiales de construcción a base de relaves mineros y cómo el concepto de MTRA se adaptaría dentro de la comunidad.
Participantes	Miembros de la comunidad, funcionarios gubernamentales.
Actividades	**Evaluación de conceptos iniciales:** Para propósitos de monitoreo y evaluación, se les pregunta a los participantes sobre los conceptos iniciales de materiales de construcción y relaves de minas para determinar el nivel de comprensión que tienen sobre los temas que se discutirán más adelante en el taller.
	Reciclaje de relaves mineros en materiales de construcción: Se presenta el tema de MTRAs. Los asistentes aprenden sobre los relaves de mina y su posible utilización en proyectos de construcción.
	Percepción de la comunidad *: En grupos, los participantes discuten sus primeros pensamientos sobre la idea de usar productos de construcción basados en relaves mineros y las posibles aplicaciones de sus experiencias y deseos particulares.
	Implicaciones ambientales y de salud: bajo una perspectiva de evaluación de la exposición, se presentan conceptos a los asistentes que explican las ventajas y desventajas del reciclaje de relaves mineros. Además, se dan consideraciones sobre cómo evaluar adecuadamente los nuevos proyectos que pueden desarrollarse en el futuro, las cosas para probar y los diferentes análisis que se pueden hacer para considerar que los productos son seguros.
	Evaluación de conceptos finales: Los resultados del aprendizaje se evalúan a la luz de la percepción de los participantes de nuevos conceptos, así como la percepción de los productos después de comprender las consideraciones ambientales y de salud pública.

* Actividades necesarias para comprender el contexto social. Se puede realizar en grupos.

APPENDIX E – COMMUNICATION WITH PROJECT DEVELOPERS

In the development of this research project, several approaches were used to communicate scientific knowledge with the international community. These include several virtual meetings with stakeholders in Colombia to explain different advances of the project and a TEDx talk that explains recycling initiatives, enduring consumption of global resources, and mine tailings.

These aforementioned activities opened the door to other approaches, among them networking with several undergraduate students from Peru and Bolivia, aiming to address this contamination issue from a fabrication standpoint, gaining not only experience in their particular needs but also in the utilization of geopolymers for the production of construction materials from an experimental perspective. The universities involved in the transfer of knowledge are:

- Universidad de Antioquia in partnership with SENA.
- Pontificia Universidad Católica del Perú.
- Universidad Católica Boliviana “San Pablo”.
- The University of Texas at Arlington (Undergraduate Research Experience).
- Colorado School of Mines (Senior Design Project).

Also, interviews with stakeholders include:

- Ministry of Environment and Sustainable Development of Colombia to study new opportunities and possibilities in the circular economy field.
- I am Gold Corporation to understand current processes in the recycling of drilling mud for bricks fabrication, social implications, and community perception.

As shown in this chapter, efforts in knowledge transfer require multidisciplinary approaches that allow stakeholders to understand the opportunities and possibilities of recycling mine tailings into useful products that society can use such as construction materials. However, these alternatives need to be developed with a critical eye, focusing on understanding the social concept in which are to be developed. Similarly, the transition of new knowledge developed in laboratories should be carried out to understand the social and political contexts that these communities may have. Efforts like the workshops presented in this section can help understand such contexts and may improve scientific communication in both directions, from academia to society by transferring better practices in fabrications methods, environmental, and health analysis, as well as from community to academia to help researchers tailor better solutions that can create meaningful impacts

APPENDIX F – TCLP TEST RESULTS

In order to develop a better understanding of the current processes developed by mine tailing recycling initiatives, a Toxicity Characteristic Leaching Procedure (TCLP) was performed to a mine tailings sample from Colombia. The sample was prepared and analyzed according to the EPA method 1311 to determine the concentration of heavy metals in the mine tailings.

First, the extraction fluid was prepared. In this case extraction fluid #1 was used. To prepare this solution three main chemicals were required, glacial acetic acid (reagent grade), reagent water, and sodium hydroxide (1N). 5.7ml of acetic acid were mixed with 500 ml of reagent water, 64.3 ml of sodium hydroxide, and tap water to dilute to a volume of 1 liter. The pH was approximately 4.90. Then, 200g of tailings were prepared and mixed with 4 liters of extraction fluid #1 to expose the heavy metals to acidic conditions for 18 hours. Four samples were taken from the TCLP test and one quality assurance (Q/A) to determine baseline concentrations of the extraction fluid. These samples were then analyzed through an Inductively coupled plasma mass spectrometry (ICP-MS) analytical test to measure the concentration of heavy metals. Also, an X-ray Fluorescence (XRF) test was performed to the undisturbed mine tailings to determine the elemental composition of the material. Results of the ICPMS and the XRF are shown in table 6 and 7, respectively.

Results show that the concentration of heavy metals after the TCLP tests were not above the limits presented by the EPA reference table (see table 8) for the contaminants of interest in this case As, Cd, Cr, Pb, Hg, Cu, Fe. These results can be attributed to the age of mine tailings, as studied by Ganesan & Sambathkumar (2003) the presence of mercury in gold mine tailings varies with time, as it is significantly reduced by vaporization processes. Considering the time during the pandemic where the material could not be tested and the uncertainty of the sample’s background (e.g., location, mine operation, principal ore extracted) it is hard to determine the accurate concentration of these contaminants.

Also, results from the XRF show consistent results to what have been found in the literature. As stated by Smiths S. & Huyck L. O. (1999), the geochemical associations, defined as the distribution of chemical elements within the earth's crust and pathfinder elements, defined as the chemical elements that are associated with a specific mineral deposit; may help identify which elements might be mobilized in tailings from specific ore deposits. As, Cu, Co, Fe, Pb, and Sb have similar geochemical signatures in most mineral deposit types, meaning that similar chemical species can be found in different mine tailings. This geochemical composition is evidenced in table 7 where Si, Fe, and Al are predominant chemical elements in the sample.

Table 6: *Results of ICPMS test performed to four samples taken from the TCLP tests and one quality assurance sample, concentration in ug/L*

	Concentration (ug/L)				
Metals	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**QA**
Ag	1	-0.18	1.1	-0.17	-0.099
Al	4900	4300	4500	4700	1.100
As	1500	1100	1800	1200	<0.16
Au	0	<0.0055	-0.018	<0.0055	<0.0055
Cd	320	320	340	340	<0.039
Cr	68	74	80	80	<0.099
Cu	760	830	860	910	1.800
Fe	4100	3700	5000	4200	-0.870
Hg	7	<5.2	7.1	4.7	<5.2
Li	-10	11	-8.5	-9.7	2.600
Mg	7100	6600	6400	7200	2.900
Mn	1800	200	2100	2200	-0.095
Ni	150	160	170	170	-0.160
Pb	280	210	280	220	-0.086
S	54000	66000	69000	78000	<1400
Zn	7900	8800	8900	9600	16

Table 7: Results of the XRF test performed on the mine tailings. This test shows the percentage of a chemical in sample

Analyte	%
Si	44.800
Fe	19.228
As	12.877
Al	7.321
S	7.128
Pb	2.903
K	1.994
Zn	1.236
Ti	0.627
Ca	0.620
Sb	0.429
Cr	0.186
Mn	0.180
Pd	0.131
Hg	0.093
Br	0.058
Cu	0.050
Zr	0.038
V	0.030
Cd	0.029
Ag	0.026
Ni	0.018

Table 8: *Reference values for the chemicals of concern of the TCLP test according to the U.S. EPA*

Chemical Element	ppm	(ug/L)
As	5	5000
Cd	1	1000
Cr	5	5000
Pb	5	5000
Hg	0.2	200
Se	1	1000
Ag	5	5000