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Reutilization, recycling and reprocessing of mine tailings, considering economic, technical, environmental and social features, a review

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Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet."

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Author

Juan Carlos Diaz Martinez

Abstract

Production of waste is one of the fundamental environmental concerns for present and future generations. It is considered an important global target. Mining industry generates extensive quantities of waste materials from ore extraction and processing plants, which accumulates in tailings and open impoundments. In 2016, Approximately 30 billion tonnes of solid mine waste were produced worldwide and more than 7 billion of these tonnes were considered mine tailings. The risks associated with mine tailings dams have different nature, namely air and soil pollution, surface and groundwater contamination by acid mine drainage (AMD) and precipitation of heavy metals. In fact, failures of tailings dams have occurred, resulting in catastrophic and irreparable environmental and economic consequences.

The need for a comprehensive framework for mine tailings management that promotes sustainable development is an important challenge facing mining companies, governments, environmental agencies and other stakeholders. This research addressed this gap. By collecting, analyzing and identifying different methods that allow mine tailings dam reutilization, recycling and reprocessing from a sustainability perspective, considering economic, technical, environmental, and social characteristics.

Keywords: mine tailings management, sustainable development, mining waste global production, legal framework.

Zusammenfassung

Das Anfallen von Abfallprodukten bildet den Kernpunkt fundamentaler Fragestellungen der heutigen Gesellschaft sowie zukünftiger Generationen. In der Bergbauindustrie fallen sowohl beim Abbau als auch der Aufbereitung von mineralischen Rohstoffen beträchtliche Mengen an Bergematerialen an, welche sich auf Halden und in Bergeteichen anhäufen. Im Jahr 2016 wurden etwa 30 Milliarden Tonnen festen Bergematerials weltweit produziert, wobei etwa 7 Tonnen davon Aufbereitungsabgänge darstellten. Das Risiko, welches mit dem Bau von Absetzbecken und Bergeteichen einhergeht, ist mannigfaltiger Natur und beinhaltet unter anderem Boden- und Luftverschmutzung, die Kontamination von Grundwasser durch saure Grubenwässer (Acid Mine Drainage), sowie das Ausfallen von Schwermetallen. Dammversagen von Bergeteichen führte in der Vergangenheit immer wieder zu schweren und teils irreparablen Schäden sowohl in umwelttechnischer als auch in wirtschaftlicher Hinsicht.

Das Erstellen eines umfassenden Rahmens für den Umgang mit Aufbereitungsabgängen zur Förderung nachhaltiger Entwicklung ist eine große Herausforderung für Bergbauunternehmen, Regierungen, Umweltämter und andere Interessensvertreter. Die vorliegende Diplomarbeit beschäftigt sich mit dem Sammeln, Analysieren und Identifizieren verschiedener Methoden, welche die Wiederverwendung von Bergeteich-Dämmen betreffen. Zudem wird auf das Recycling und die Wiederaufbereitung von Aufbereitungsabgängen unter dem Gesichtspunkt der Nachhaltigkeit eingegangen, wobei auch wirtschaftliche, technische, umweltrelevante, und soziale Aspekte einfließen.

Schlüsselbegriffe: Umgang mit Aufbereitungsabgängen, nachhaltige Entwicklung, weltweite Produktion von Bergematerial, gesetzliches Regelwerk.

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1. INTRODUCTION AND RESEARCH PROBLEM

1.1. Problem Statement

Production of waste is one of the main environmental problems and a critical challenge for present and future generations. It is considered an important global target, especially in the United States and the European Union (Johansson and Corvellec, 2018). In 2002, Governments recognized the importance of solid waste management at the World Summit on Sustainable Development, in Johannesburg, South Africa, where, one of the most important topics on the agenda was to develop strategies for prevention, minimization, reuse and recycling of waste (Lottermoser, 2011).

The need and value for metals and minerals have significantly increased due to the exponential growth in the world population which has resulted in the processing of high volumes of mineralized material and subsequently producing huge amounts of waste rocks and especially mine tailings (Lottermoser, 2010; Afum et al., 2018; Gorakhki and Bareither, 2017; Kefeni et al., 2017; Dold, 2008; Kossoff et al., 2014; Kesler, 2002). The term “Mine Tailings” is used to classify the material that results from the extraction and recuperation process of minerals, which is not profitable or worthless based on current market conditions and technology (Adiansyah et al., 2015; Afum et al., 2018).

There is an estimation of 20 – 25 billion tonnes of solid waste produced annually worldwide and around 5 - 7 billion of these tonnes are considered mine tailings. The amount of tailings generated by mines can be almost equal to the amount of raw materials processed. In some cases, when low grade ore metals are extracted, more than 99% of the original material might end up in the tailings. (Lottermoser 2011; Adiansyah et al., 2015; Edraki et al., 2014). The problematic with mine tailings is that the large volume of tailings dams can cause enormous environmental footprint. Apart from a strong visual impact, other important aspects, such as chemical, physical and geotechnical instability can cause accidents with severe and long term economic, environmental and social consequences (Mulligan et al., 2011; Rangeial, 2011; Lottermoser, 2011). This is why proper management of tailings has become a crucial issue in mining operations.

Tailings dam failures have occurred and caused fatalities and considerable environmental damages. From 1917 to 2009, there have been more than 230 cases of tailings accidents around the world, some of them with shattering consequences (Lottermoser, 2010). Just at the moment of writing this thesis occurred the Brumadinho dam disaster, in Minas Gerais, Brazil. On Friday, January 25, 2019, the Brumadinho tailings dam No. 1 of Vale's failed, discharging around 12 million cubic meters of tailings. The slurry wave killed more than 200 people, and many others have been reported missing. Apart from the incalculable loss of lives, the slurry released destroyed all life in the river "Rio Paraopeba" and inhibits production of drinking water in all the communities along it. The Brumadinho disaster has been the second in the region since 2015, when Fundão Tailings Dam, co-owned by Vale collapsed (BBC, 2019). In addition to the risk of catastrophic events, active and abandoned tailings dams can also release toxic effluents and other potentially hazardous materials into the environment such as acid mine drainage (AMD) which is very toxic to aquatic organisms, animal and plants, also its high risk to human health is an important concern (Figueiredo et al., 2018). Considering the severe consequences that can be produced by inappropriate tailings dam management mentioned above, the necessity for developing optimum methodologies for proper and sustainable reclamation of mining tailings are indispensable.

Most of the solid mine waste produced worldwide is pumped into tailings storage facilities (TSF). The most common methods for tailings disposal cover: backfilling into open pit or underground mines, hillside dams or cross valley, dry-stacking of thickened tailings on land and raised embankments/impoundments. Additionally, there is another practice less popular due to the negative impacts occasioned to the environment, which is direct disposal of mine tailings into rivers, lakes and the ocean, in some cases with no previous treatment, this practice is applied in a few countries such as Papua New Guinea, Indonesia and Norway (Edraki et al., 2014; Schoenberger, 2016). According to Lottermoser (2011), there are more than 3,500 tailings storage facilities around the world with different sizes; from a few meters to thousands of square meters. In fact, due to their size, they leave the largest footprint of any mining activity on the landscape.

In order to deal with the consequences of poor mine tailings management the Ministerial Council on Mineral and Petroleum Resources (MCMPR) and the Mineral

Councils of Australia (MCA) in 2003, established several principles for the correct management and disposal of mine tailings, these principles include: adoption of a risk-based approach, minimizing tailings production and increasing tailings reuse and considering economic, environmental and social aspects (Adiansyah et al., 2015). The last principle mentioned above will be the focus of this investigation.

Reutilization, recycling and reprocessing of mining tailings have many advantages, such as limit waste production, decrease the cost of waste treatment and disposal, create financial assets, develop local industry, create jobs and at the same time could change the perception of the mining industry, making the mining business much environmentally friendly (Lottermoser, 2011). The need for finding new techniques for mine tailings reclamation which reduce the volume of tailings available and at the same time generate economic value for mining industry and society, and promote preservation of the environment are crucial and will be addressed in this research.

1.2. Significance of the Research

Reclamation and proper management of mine tailings has become a fundamental part for modern mines, governments and other important stakeholders. It can be evidenced in new mining and environmental legislations which every time is stringent in relation to the treatment and disposal of mine wastes. Nevertheless, the great majority of waste produced by the mining industry is still placed in tailings storage facilities at mine site as well as their associated risks (Hudson et al., 2011).

The current methods implemented for tailings disposal and storage have their own advantages and disadvantages in terms of economic, technical, environmental and geotechnical stability. However, they do not deal with the real concern of tailings, any of these methods reduce the volume of tailings, these practices just placed the mine tailings into storage facilities at mine site, keeping a high potential risk to leave environmental, social and economic legacies for hundreds of years. Additionally, these methods do not produce any financial asset. In fact, the process of reclamation of tailings using traditional methods results in a vast investment for mining companies in terms of treatment and monitoring of tailings dams (Lottermoser, 2011; Mulligan et al., 2011).

This investigation will address the gap identified above. There is a present need to implement more research in this field in order to find new methods or applications for reutilization of mine tailings which reduce the volumes of mining solid waste generated and consequently decrease the risks of environmental and social effects. This research intends to show that mine tailings can become a valuable commodity, either because the implementation of new technology which allows to recovery metals that still place into the mine tailings dams and have economic value, or recycling tailings into a new product or application. Both solutions have positive effects: they improve the employability of local communities, develop local industry, decrease the costs associated with solid waste treatment and disposal, enhance environment conditions and could change the public perception about the mining business in order to facilitate the achievement of the social license.

1.3. Objectives

The overall aim of this thesis is to identify different methods for mine tailings reutilization, recycling and reprocessing from a sustainable perspective, considering economic, technical, environmental and social aspects.

Specific objectives:

- Identify different methods for mine tailings reutilization, recycling and reprocessing from the literature.

- Analyze some technical parameters of mine tailings dam from the literature in order to establish applications for mine tailings reuse, recycling and reprocessing.

- Determine the main mineral commodities that can be used for utilization, recycling and reprocessing of tailings dam, according to the current market and technological conditions.

- Review of the general aspect of mine tailings legal framework in some countries where mining industry is considered an important economic activity.

1.4. Limitations of the Research

According to Lottermoser (2011), the most important problem regarding scientists working in the field of reutilization, recycling and reprocessing of mine wastes is the quantification and classification of all the elements that can be found in mine wastes, in this specific case in tailings dams. This study addresses the classification of mine tailings dams, according to their technical parameters. However, the chemistry and mineralogy of tailings must be identified in order to understand their long term behavior. Consequently, to explain the distribution and occurrence of all elements existing in tailings dams and their behavior in all scales are the major limitations of this investigation.

Furthermore, analysis and collection of existing data turn out to be a great challenge in order to establish a methodology for proper management to reuse, recycle and reprocess mine tailings dams.

2. LITERATURE REVIEW

2.1. Introduction

In 1503, the famous German Carthusian humanist writer Gregor Reisch, in his celebrated encyclopedia "*Margarita Philosophica*", highlighted the importance of mining. Since the beginning of civilization, humans have exploited minerals and elements, such as rocks, industrial minerals, gemstones, coal and metals among others, mainly for the production of goods, energy and building materials. In fact, the Chalcolithic (Copper) Age and the "Golden Age" owe their names to mining. The first one took its name for the exploitation of copper and the production of tools and weapons while the "golden age" took its name for the exploitation of gold from the mines in Latin America (Edwards et al., 2011). Mining is an ancient activity which has been helping to literally build the modern society. It is impossible to imagine the contemporary society without the minerals extracted and processed by the mining industry.

The mining industry is one of the most important economic activities worldwide. It contributes to trillions of dollars annually to the world economy by providing raw materials for industrial and domestic consumers (Lottermoser 2010; Falagán et al., 2017). Mining activity has considerably increased in the last decades as well as the environmental challenges related to the proper management of waste (Aznar et al., 2018; Gorakhki & Bareither 2017). The exploitation of mineral resources to meet current needs has resulted in the processing of a large amount of mineralized materials which at the same time produce high volumes of solid and liquid wastes, known popularly as "mine wastes" (Afum et al., 2018). Almost every country has or has had a mining industry and, as a result, has a legacy of mine waste. Consequently, the vast production of mine wastes that come from the industrial mineral processing plants and their inappropriate reclamation has occasioned many problems of global importance (Edwards et al., 2011).

Mineral processing plants produce two kinds of products; economic and non-economic, the last one is usually known as "mine tailings" which is composed of water, chemicals, organic material and small quantity of minerals. These tailings generated by the mining industry are considered wastes because they are not profitable based on several circumstances, such as current economic conditions, existing technology, environmental and governmental policies (Adiansyah et al., 2015). Mine tailings basically consist of gangue from which most of the valuable minerals have been removed. However, mining recovery processes are not 100 percent efficient, and mine tailings always contain small quantities of profitable minerals. Indeed, there have been documented some cases where tailings storage facilities have very high concentrations of valuable minerals reason for which some of them have been reprocessed (Edwards et al., 2011).

Some researchers agree that the amount of tailings generated by mines can be almost equal to the amount of raw materials processed. For example, a mine producing 200,000 tonnes of copper ore per day will also produce nearly the same tonnage of tailings per day. According to Lottermoser (2010), exploitation of metalliferous mineral resources aims to recover only a few parts per million values of gold and small percent concentrations of some minerals, such as lead, copper or zinc. The great majority of the total removed and processed material is generally rejected and classified as processing and metallurgical waste, and consequently storage at the mine site (Lottermoser 2011; Edraki et al., 2014; Adiansyah et al., 2015; Kinnunen et al., 2018).

Mine tailings impoundments are one of the most important concerns for the mining industry, not just because of the sheer volume and aerial extent which can oscillate between meters or kilometers square, but, because they can release potentially harmful elements to the ecosystems and cause severe and irreparable environmental effects (Lottermoser, 2010). This is why proper management of mine tailings disposal and treatment has become an important target for the mining industry and governments worldwide.

2.2. Tailings Storage Facilities (TSF)

The mine waste management hierarchy (Figure 1) is a well-established guide to prioritizing waste management practices, showing the most favored approach at the top to the least favored approach at the bottom. As shown in Figure 1, minimization of mine waste is the most preferred choice, whereas treatment, disposal and storage are the least favored options. Nevertheless, the most common approach used in conventional mining and waste management is the treatment, disposal and storage options (Lottermoser, 2011; Afum et al., 2018).

Tailings storage facilities or popularly known as “tailings dams” can be defined as sedimentation lagoons where residues that result from the mining process of mineral recuperation, including water, are disposed and stored. The speedy growth of the metal mining industry over the last few decades has made the construction of tailings dams of bigger dimensions than before (Valenzuela, 2016). It is estimated that there are at least 3,500 tailings dams spread all over the world (cp. Davis and Martin et al., 2000. In Lottermoser, 2010).

Figure 2, shows a simplified scheme of a tailings dam. Each technique or method used to build a tailings dam has it owns advantages and disadvantages based on geological, seismic stability, application, technical, economic and environmental conditions, among others. The next section of this research is a summary where a brief description of each method is presented.

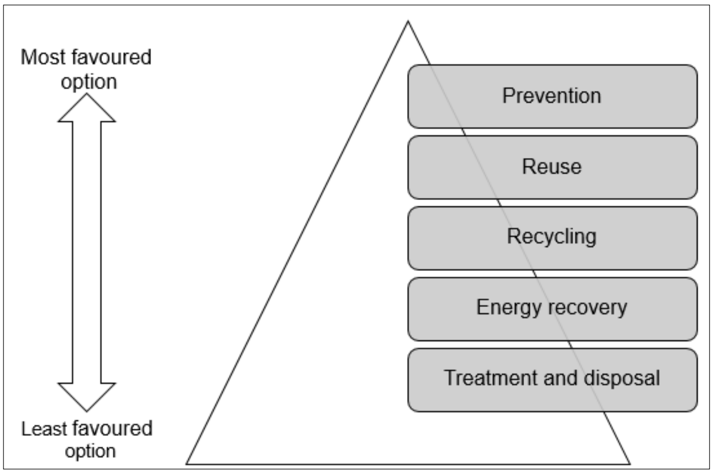

Figure 1. Mine waste management hierarchy (Lottermoser, 2011).

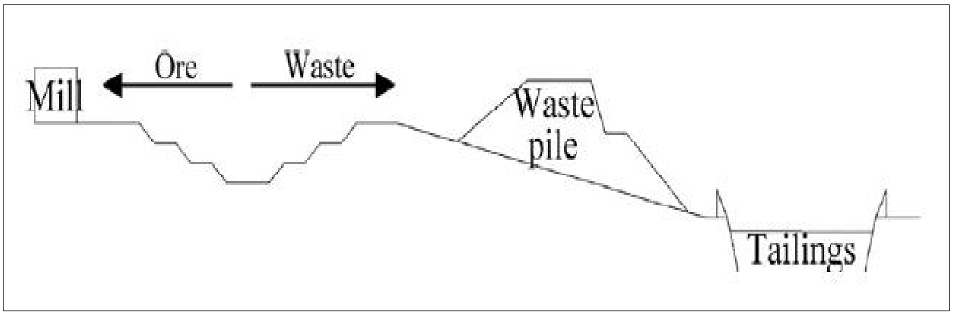

Figure 2. Simplified scheme of a tailings dam (Afum et al., 2018).

2.2.1. Raised Embankment / Impoundment Designs

The raised embankment, or impoundment methods for tailings disposal are considered the most conventional methods for tailing storage facilities. The three principal designs are downstream, centerline and upstream structures, being the last one the most popular. In fact, more than 50% of the tailings dams worldwide are built using this variation. These three main designs determine in which direction the embankment crest moves in relation to the start point of the dike at the base of the dam wall (U.S. EPA, 1994).

Upstream tailings dams are built progressively of the starter dike by incorporating tailings materials into the dam for support, through the controlled deposition of tailings. The construction of a starter dike foundation is the first step for an upstream designed embankment. Tailings are usually discharged from the top of the dam crest creating a “spigotted tailing beach” that becomes the foundation for future embankment raises. The basic steps for the construction of an upstream raised embankment is illustrated in figure 3. This method is the most popular due to the minimal amount of fill material required for its construction and subsequent raising, which normally involves totally of the coarse fraction of the tailings. Upstream is considered the cheapest and the simplest method for tailings disposal. However, it is considered the most unstable method for tailings storage facility (Valenzuela, 2016).

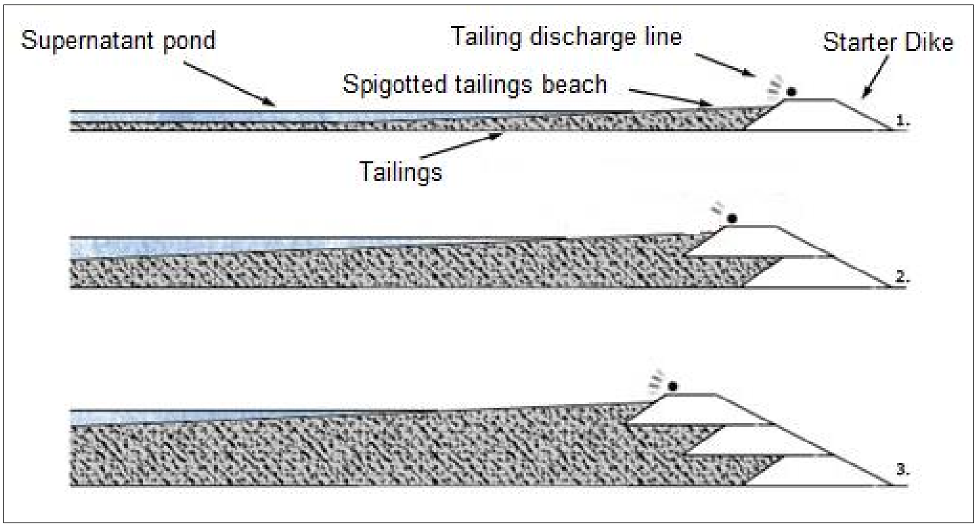

Figure 3. Upstream method of embankment for tailings disposal (US EPA, 1994).

2.2.2. Backfilling

According to the European Commission, in a report published in 2009, about "Management of Tailings and Waste-Rocks in Mining Activities", backfilling is considered one of the best available techniques for mining tailings disposal (EC, 2009). Backfilling consists in the reinsertion of materials into the mining voids. These materials are typically tailings, waste-rock and overburden, either alone or in combination with other structural products, such as cement or binding agents. There are four variations of this method; cemented backfilling, dry backfilling, hydraulic backfilling and paste backfilling. In general this method could be used for both; underground and open pit mining, even can be used in abandoned pits or in portions of active pits (Mulligan et al., 2011; EU, 2009).

Backfill is a technique used for different proposes basing on the mining methods. For example, for underground mine backfilling is used mainly for improving and assure the condition of underground stability, reduce or avoid subsidence in the underground and on the surface, provide roof support in order to improve safety conditions and also to extract further parts of the ore body, provide an alternative to surface disposal and in some cases in order to improve ventilation. While, in open pits, backfill is used mostly for improved safety conditions by minimizing risk of collapse by backfilling the pit instead of building a new pond or heap (Afum et al., 2018; EU, 2009).

Nonetheless, this method also has some disadvantages. For example, not all the tailings produced at a mine can be used by backfill due to the increase in volume from size reduction separations, a maximum of about 50% of the tonnage extracted can be used as backfill. It means that in cases where the ore grade is less than 50% it will not be possible to backfill all the tailings. Moreover, the application of these methods can be limited due to their high cost of implementation related in most of the cases with the use of binding agents, high costs of transportation and energy, the costs of double handling. Furthermore, there are other factors that can limit the application of backfilling such environmental considerations like seepage as well as issues related to temporary storage (Mulligan et al., 2011; EU, 2009).

2.2.3. Thickened and Paste Technology

Thickened and paste disposal of mining tailings is considered an alternative method for minimizing the environmental footprint generated from conventional tailings storage facilities. This method removes a significant proportion of water from the tailings, about 50-70%, in order to produce slurry (paste) with a high density (EU, 2009; Lottermoser 2010). The implementation of thickened tailings methods requires the use of mechanical equipment known as “the thickeners” to dewater tailings. Mine tailings are then spread in layers over the storage area by the thickener in order to allow further dewatering through a combination of drainage and evaporation. Tailings are conventionally thickened and then filtered to form a paste that looks like a “wet cake” (Figure 4). Then, this material is re-pulped under closely controlled conditions to accurately prepare a paste with the proper consistency, during this process some elements are added in order to neutralize the paste and avoid undesirable chemical reactions, such as acid mine drainage (Edraki et al., 2014).

Advantages of thickened and paste technology included; maximizing the density of tailings, minimize the footprint by reducing the area for tailings storage facilities because this technique does not cover large extensions of land as conventional methods of tailings dams. In some cases, reclaim and safe water, energy and process reagent. Also, reduce the risk of acid mine drainage by removing water available for leaching, decreasing permeability and oxygen diffusion. Furthermore, concentrate tailings suitable for mine backfill and minimize the risk of dam failures, water run-off and leaching (Edraki et al., 2014; Lottermoser, 2010).

Doubtless, the potential for water recovery and limitation of longer term environmental impacts remains attractive. Nevertheless, this technology is still largely reserved for underground backfill operations. Some Factors, such as the high costs of equipment and the necessity to maintain a stable operation have limited its application in surface disposal. Furthermore, the unreasonably large percentage of clay particles in thickened tailings are considered a critical factor. If clay minerals are presented and mine tailings are raised too high and fast there is a high risk of tailings dam failures (Watson et al., 2010; Edraki et al., 2014).

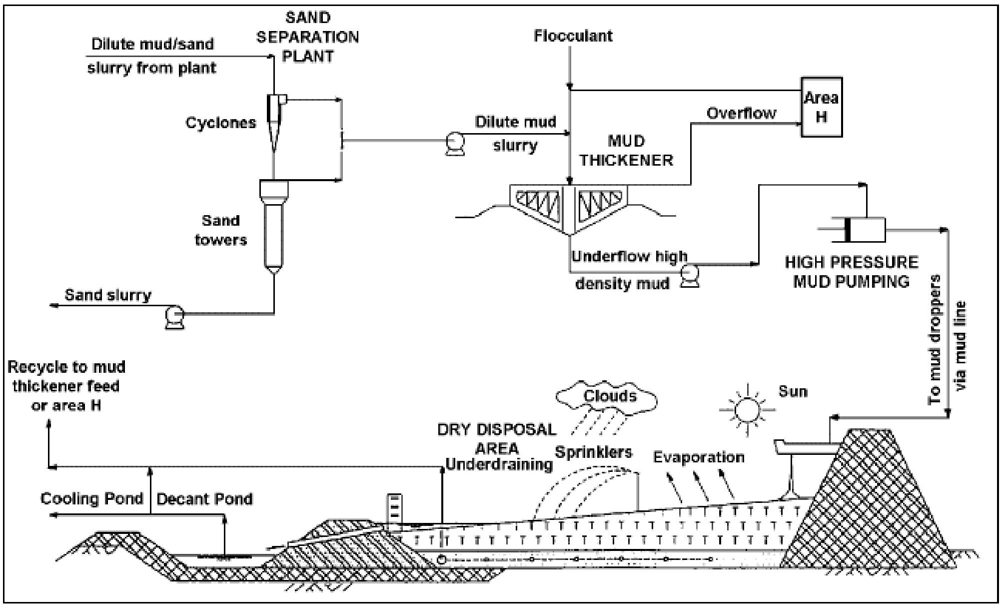

Figure 4. Schematic drawing of thickened tailings management operation (EC, 2009).

2.2.4. Direct Disposal of Mine Tailings

This method consists in direct discharge of mine tailings into rivers, lakes and the ocean, in some cases with no previous treatment. This practice is unusual, but is still applied in some countries, such as Papua New Guinea, Indonesia and Norway (Edraki et al., 2014; Schoenberger, 2016). The aim of direct disposal is to use the minimal concentration of oxygen that exist in marine environments in order to storage the tailings into the ocean, also to prevent tailings from entering in contact with the shallow, biologically productive and oxygenated zone (Lottermoser, 2010).

This method has been used in artisanal mining and other industrial operations which have demonstrated the terrible consequences that the application of this practice can produce. For example, this method can cause the increase in metalloid and metal concentration of sediments, vegetation and water, resulting in the destruction of flora and fauna in some habitats. Mine waste, particularly tailings, is generally not inert and must be isolated from interacting with the environment. Some processes such sedimentation, generation of acid mine drainage, cyanide and metal mobilization can change the physical and chemical properties of rivers and oceans, increasing the risk of flooding of surrounding vegetation originating irreparable damages to aquatic ecosystems (Mulligan et al., 2011; Lottermoser, 2010).

2.3. Major Concerns with Traditional and Current Tailings Dams

Impoundments are useful and necessary repositories for tailings. However, they are a common challenge facing not only mining companies, but also governments, environmental authorities and other stakeholders worldwide. This mainly because tailings storage facilities can create environmental problems. There are several major and minor environmental concerns related to tailings dams. According to research the most important environmental impacts generated by mining tailings storage facilities are: tailing dam failures, acid mine drainage generation, visual impact, as well as air and soil pollution through dust generation (Lottermoser, 2010; Kossoff et al., 2014; Schoenberger, 2016).

2.3.1. Tailings Dam Failures

The purpose of the construction of a tailing dam is to contain waste material for an indeterminate period. Tailings storage facilities should be designed to prevent failures of tailings dam structures, to secure long-term stability against erosion and mass movement, to prevent environmental contamination of surface and ground waters, and at the end of the mine life to return the area for future land use (Lottermoser, 2011). However, tailings dam failures account for about three-fourths of major mining-related environmental disasters (Schoenberger, 2016b). According to the International Commission on Large Dams (ICOLD) (2001), mine tailings dams are more vulnerable than other retention structures and are considered a major threat because of the following reasons: first of all, their unstable nature (principally for those built with earth). Secondly, because of their location (often situated near sensitive aquatic ecosystems and communities). Third, their large number and in some cases their long dimensions (in the tens of thousands worldwide) and finally, due to their poor or non-existent maintenance, especially after the closure of mining activities and particularly in developing countries where environmental mining regulation is more flexible.

Since 1960, over 100 major failures of tailings dams have been documented worldwide (See Table 1). For example, in 1928, the Barahona tailings storage facility in Chile failed during a large earthquake, killing more than 50 people in the ensuing flow failure. In 1976, the Bafokeng platinum tailings storage facility in South Africa collapsed after a period of above average rainfall, releasing more than 3 million tonnes of tailings during the resulting flow slide, causing the deaths of 12 people (Fourie, 2009). Recent events, such as Baia Mare catastrophe in Romania in 2000, which resulted in the release of 100,000 m^3 of cyanide contaminated liquid into the Lapus stream and the subsequent lodging of $179 million compensation claim by the Hungarian government against the mine owners, and the two latest major tailings disasters, both in Brazil; the disaster of Fundão tailings dam in Bento Rodrigues, in 2015. Where more than 43 million m^3 of iron tailings (80% of the total contained volume) were released to the environment, killing 19 people and causing irreversible environmental damage to hundreds of water-courses in the basin of the Doce River and associated ecosystems. Also, the disaster of Brumadhino dam, which killed more than 230 people, in 2019 (figure 5) (Carmo et al., 2017; BBC, 2019).

The environmental and economic impacts of mine tailings dam failures can be in order of different magnitudes. It depends on the size and volume of tailings and the kind of mineral storage into the dams. The most shattering consequence of an immediately dam failure is the death of people. Research indicates that thousands of people have died from tailings dam failures. For example, around 4,000 people were killed in the flood resulting from the March 1626 failure of the San Ildefonso dam in Potosí, Bolivia. And, at least 260 people died in the failure of the fluorite tailings dam in Stava, Italy, in 1985. In the immediate repercussion of a severe dam break the deaths reported are largely the results of drowning and suffocation (Kossoff et al., 2014; Lottermoser, 2010).

Tailings dam breaks can contaminate natural waters in the short term, impacts on flora and fauna can be just as severe due to a combination of burial, mud blocking and the extreme change in the chemical and physical characteristics of water sources. As an example, on 25 April 1998, about 1.3 x 10^6 m^3 of tailings were deposited over 26 km^2 of the Guadiamar River Basin following the breach of the Aznalcóllar dam in Spain. For instance, as a direct result of the spill, all of the fish in the polluted watercourses were killed. 37 tonnes of dead fish were collected in the month following the accident. Furthermore, as indirect result more than 4,000 hectares (ha) of land were contaminated by the Aznalcóllar breech, of which around 2,500 ha were used for agricultural activities. All agricultural products from the affected area were harvested for destruction due to the precipitation of heavy metals and acidification (UNEP, 2017).

On the other hand, contamination of soils and sediments are not less intense that contamination of water sources. Alluvial floodplains are fertile environments which support flora and fauna, and crop production. Floodplain contamination by metal and metalloid elements is usually an unavoidable result of tailings dam failures. Many of these elements that are included in tailings dams are potentially toxic to the biosphere in general as well as for humans. For example, on 25 August 1985, a tailings dam collapsed inundating the Dong River valley in China. As a result, strips of farmland 400 m wide along both river banks were covered with a 15 cm thick layer of black sludge. Cleanup efforts were not enough to remediate the damage on the impacted land, leaving some hectares of land for agricultural purposes destroyed. 17 years later, in August 2002, the polluted soil showed concentrations of heavy metals far in excess of the Chinese soil maximum allowable concentration standard (Liu et al., 2005; Kossoff et al., 2014). These examples show the magnitude of the negative impact that can be reached for tailings dam failures disaster.

Although environmental and social impacts are the most important issues for the media and scientists. The economic, social and political consequences of tailings dam failures are major concerns for the mining business. There are two important economic concerns of dam failures, which are business interruption (down time of mining and processing operations) and environmental damage and cleanup. For example, in the Aznalcóllar disaster in Spain, it was estimated that the Andalusian Government and the Spanish Environmental Ministry had spent more than 276 million Euros on the cleanup. To date they have received no compensation from Boliden, the mining company responsible for the disaster. The Government is still trying to obtain at least 134 million Euros from this mining company. Another example, is the disaster of the Fundão tailings dam in Bento Rodrigues where the companies (Vale and BHP) had to pay more than 4 billion dollars just for cleaning and for the interruption of mining operations. More than 3 years have passed from the disaster and the mine still with not operation at all. This situation has resulted in millions dollar of loss for the company and also for many members of the community which lost their jobs at the company and with this their main source of incomes (Kossoff et al., 2014; Carmo et al., 2017).

Finally, but not less important there are the socioeconomic and political impacts associated with transboundary migration of effluent in rivers which sometimes take place in tailings dam failures. For example, the Baia Mare and Baia Borsa incidents in Romania, that affected Hungary and the former Yugoslavia. This caused cyanide compounds to enter the Lapus river and from there enter the Tisza, one of Hungary's largest rivers, and the Danube upstream of Belgrade, and finally the Black Sea. This tailings dam failure has resulted in a transboundary pollution situation which could have had serious influences on biodiversity, the aquatic ecosystems, water sources and the socioeconomic conditions of different communities in three different countries (Kossoff et al., 2014).

The death of thousands of people, the irreparable environmental impacts, the social and the economic consequences for the communities and the mining company itself are some of the major concerns of mining tailings dam failures. This is one of the main reason why proper management of mine tailings has become an important issue for contemporary mines and stakeholders.

Figure 5. Brumadhino, Brazil, after a tailings dam failure (Bierly, 2019).

Date	Location	Incident	Environmental Impact and Fatalities
2019, Apr. 09	Jharkhand, India	Failure of red mud tailings pond	Spill of red mud over 35 acres. No casualties reported
2019, Mar. 29	Rondônia, Brazil	Failure of abandoned Tin dam after heavy rain	Damaged of seven bridges. No fatalities reported
2019, Jan. 25	Brumadinh, Brazil	Failure of iron tailings dam	Released of at least 12 million m^3 of tailings. 231 people were killed, and 41 are reported missing
2018, Jan. 04	Urique, Mexico	Failure of gold and silver tailings dam	Released of at least 250,000 thousand m^3 of tailings. 3 workers were killed, and 4 are reported missing
2018, Mar. 03	Recuay, Peru	Failure of polymetallic tailings dam after heavy rain	Released of 80,000 m^3 of tailings. No fatalities reported
2017, Mar. 12	Hubei, China	Partial dam failure	Approximately 200,000 m^3 of tailings were liberated. 2 people were reported dead and 1 was reported missing
2017, Sep. 17	Bong County, Liberia	Rupture of a gold tailings dam after heavy rain	Discharged of 11,500 m^3 of slurry containing cyanide. 30 people were reported sick
2017, June. 30	Mishor Rotem, Israel	Phosphogypsum dam failure	100,000 m^3 of acidic waste water were released
2016, Aug. 08	Luoyang, Henan province, China	Failure of a bauxite tailings dam	Village totally submerged in red mud, around 300 villagers were evacuated
2015, Nov. 21	Hpakant, Kachin state, Myanmar	Jade heap failure	More than 110 people were killed
2015, Nov. 05	Bento Rodrigues, Brazil	Failure of the iron Fundão tailings dam	Destroyed 158 homes and 15 square kilometers of land. At least 17 persons were killed and 2 are reported missing
2014, Aug. 04	British Columbia, Canada	Copper and gold tailings dam failure due to foundation failure	7,3 million m^3 of tailings. 10,6 million $m^3$of water, and 6,5 million m^3 of interstitial water were released

2014, Sep. 10	Região Central, Minas Gerais, Brazil	Iron tailings dam failure	two workers killed and one missing
2013, Oct. 31	Northeast of Hinton, Alberta, Canada	Breach of wall in coal pond	670,000 m^3 of coal wastewater and 90,000 tonnes of muddy sediment were discharged
2012, Aug. 01	Itogon, Benguet province, Philippines	Breach in Copper and gold tailings pond during heavy rains	20.6 million tonnes of tailings were released
2011, Jul. 21	Mianyang City, Songpan County, Sichuan Province, China	Manganese tailings dam damaged from landslides caused from heavy rains	Tailings damaged residential roads and houses, forcing 272 people to leave
2010, Oct. 04	Kolontár, Hungary	Bauxite tailings dam failure	700,000 m^3 of caustic red mud were liberated and 10 people killed and approx. 120 people injured
2009, Oct. 29	Karamken, Magadan region, Russia	Gold tailings dam failure after heavy rain	11 homes were carried away by the mudflow; at least 1 person was killed
2008, Sep. 08	Taoshi, , China	Collapse of an iron dam at an illegal mine during rainfall	277 people were killed and 33 were reported injured.
2007, Jan. 10	Miraí, Minas Gerais, Brazil	Bauxite tailings dam failure after heavy rain	2 million m$^{3\ \mathrm{of}}$ mud were released. No fatalities.
2006, April. 30	Miliang, Shaanxi Province, China	Gold tailings dam failure during sixth uprising of dam	17 people killed
2005, April. 14	Bangs Lake, Jackson County, Mississippi, USA	Phosphogypsum stack failure,	Approximately 17 million gallons of acidic liquid were discharged
2004, Nov. 30	Pinchi Lake, British Columbia, Canada	Mercury tailings dam collapsed during reclamation work	Material spilled into 5,500 ha Pinchi Lake

2003, Oct. 03	Cerro Negro, Quinta región, Chile	Copper tailings dam failure	50,000 tonnes of Tailings released
2002, Aug. 27	San Marcelino, Philippines	Failure of 2 abandoned Copper and silver tailings dams after heavy rain	Villages flooded with mine waste; 250 families evacuated. Anyone reported hurt or kill
2001, Jun. 22	Sebastião das Águas Claras, Minas Gerais, Brazil	Iron mine waste dam failure	2 mine workers were reported killed and three more workers are missing
2000, Jan. 30	Baia Mare, Romania	Gold tailings dam crest failure after heavy rain	100,000 m^3 of cyanide-contaminated liquid released. killing tonnes of fish and poisoning the drinking water of more than 2 million people in Hungary
2000, Oct. 18	Dachang, Guangxi province, China	Failure of upstream tin dam	28 people killed and more than 100 houses destroyed
1999, Apr. 26	Placer, Surigao del Norte, Philippines	Gold tailings spill	700,000 tonnes of cyanide tailings released. 17 homes buried.
1998, Apr. 25	Los Frailes, Aznalcóllar, Spain	Polymetallic dam failure from foundation failure	4-5 million m^3 of toxic water and slurry released and thousands of hectares of farmland destroyed
1997, Oct. 22	Pinto Valley, Arizona, USA	Copper tailings dam slope failure	230,000 m^3 of tailings liberated and 16 ha covered
1996, Mar. 24	Marinduque Island, Philippines	Loss of Copper tailings from storage pit through old drainage tunnel	1.6 million m^3 of tailings liberated. Evacuation of 1,200 residents, 18 km of river channel filled with tailings and US$ 80 million in damage
1995, Sep. 02	Placer, Surigao del Norte, Philippines	Gold dam foundation failure	12 people killed
1994, Feb. 22	Merriespruit, South Africa	Gold tailings dam wall break following heavy rain	17 people killed

1993, Oct.	Marsa, Peru	Gold tailings dam failure	6 people killed
1992, Jan.	Luzon, Philippines	Collapse of Copper dam wall	80 million tonnes of tailings were released
1991, Aug. 23	Kimberley, British Columbia, Canada	Lead and zinc dam failure	75,000 m^3 of tailings were discharged
1989	Ok Tedi, Papua New Guinea	Collapse of waste rock and tailings dam	Released of 170 million tonnes of waste rock and 4 Mt of tailings
1988, Apr. 30	Jinduicheng, China	Breach of molybdenum dam wall	Approximately 20 people killed
1987, Apr. 08	West Virginia, USA	Coal dam failure	87,000 cubic meters of water and slurry released
1986	Huangmeishan, China	Iron dam failure	19 people killed
1985, July. 19	Stava, Trento, Italy	Fluorite dam failure	More than 260 people killed and 62 buildings destroyed
1982, Nov. 08	Sipalay, Philippines	Copper dam failure	Widespread inundation of agricultural land. More than 28 million tonnes of tailings discharged
1981, Dec. 18	Ages, Kentucky, USA	Coal dam failure	More than 96,000 cubic meters of coal slurry liberated. 1 person was killed and 3 homes destroyed
1980, Oct. 13	Tyrone, New Mexico, USA	Copper dam wall breach	At least 2 million m^3 of tailings released
1979, July. 16	Church Rock, New Mexico, USA	Uranium dam wall breach	370,000 m^3 of radioactive water discharged
1978, Jan. 14	Arcturus, Zimbabwe	Gold slurry overflow after continuous rain	1 person killed
1977, Feb. 01	Milan, New Mexico, USA	Uranium dam failure	30,000 m^3 of radioactive water discharged

1976, Mar. 01	Zlevoto, Yugoslavia	Lead and zinc dam failure	300,000 m^3 of tailings discharged
1975, June	Silverton, Colorado, USA	Dam failure	Tailings flow slide polluted nearly 160 km of the Animas river.
1974, Nov. 11	Bafokeng, South Africa	Platinum dam failure	12 people killed and 3 million m^3 of tailings were discharged
1973	Southwestern USA	Copper dam failure	170,000 m^3 of tailings were liberated
1972, Feb. 26	Buffalo Creek, West Virginia, USA	Coal dam disaster	125 people died and 500 homes were destroyed
1971, Dec. 03	Fort Meade, Florida, USA	Clay pond dam failure	9 million m^3 of clay water released into the Peace River
1970	Mufulira, Zambia	Copper tailings dam disaster	98 miners killed and more than 1 million tonnes of tailings discharged
1969	Bilbao, Spain	Dam failure because heavy rain	115,000 m^3 of tailings released
1968	Hokkaido, Japan	Dam failure during earthquake	90,000 m^3 of tailings released
1967, Mar.	Florida, USA	Phosphate dam failure	250,000 m^3 of tailings reached Peace River
1966, Oct. 21	Aberfan, Wales, United Kingdom	Coal dam failure	144 people were killed
1966, May. 01	Sgorigrad, Bulgaria	Polymetallic dam failure	Destroyed half of Sgorigrad village, killing 488 people
1965, Mar. 28	El Cobre, Chile	Copper dam disaster	Killed more than 200 people
1962, Sep. 26	Huogudu, Gejiu, Yunnan, China	Tin dam failure	Destroyed 11 villages, 171 people were killed and left almost 14,000 homeless

Table 1. Chronology of major tailings dam failures since 1962 (Lottermoser, 2010; WISE, 2019).

2.3.2. Acid Mine Drainage (AMD)

The problem of sulphide oxidation and the associated acid mine drainage (AMD) or acid rock drainage (ARD) has been a major focus of research over the last 50 years. Acid mine drainage is a major problem all over the world. The term AMD is commonly used (than ARD) because the process occurs mainly at mining sites. It occurs in both operating and abandoned polymetallic sulphide mining sites (Simate and Ndlovu, 2014). The main source of AMD is oxidation of sulphide mineral ores, which are initially exposed to the environment by intensive mining activities. In particular, among the metal sulphides, pyrite ore (FeS_2, commonly known as fool's gold) is one of the main mineral responsible for generation of AMD due to its simplicity of oxidation when it is exposed to oxygen, water and microorganisms (Kefeni et al., 2017).

It has been proved that tailings may have high sulfide content in the form of rejected pyrite and other sulfide minerals. If these tailings are exposed to atmospheric oxygen or superficial and/or underground water this situation may cause sulfide oxidation and activate the process of generation of acid mine drainage. Acid production and acid buffering reactions as well as secondary mineral formation could happen, and low pH values on the water with high concentration of dissolved constituents will be generated. Tailings dams are more likely to generate AMD than waste rocks because they have a much higher specific surface area available for oxidation and leaching reactions (Lottermoser 2011).

AMD contains high concentrations of acid and dissolved metals. When this toxic mixture flows into groundwater, streams and rivers, it gives rise to several environmental problems. Toxicology and epidemiological studies revealed that elements in AMD are hazardous to living organisms on exposure. AMD is toxic to aquatic organisms, destroys ecosystems, corrodes infrastructure, and spots of water in regions where fresh water is already in short supply. The uptake of toxins from mine waste–affected soils and waters can lead to their bioaccumulation and bio magnification in terrestrial plants and aquatic organisms. Plants and crops grown on contaminated soils often contain high concentrations of metals. Animals grazing on alluvial soils often eat this plant material and sediment, especially after flooding when fresh metal-rich sediment is deposited. This situation represents a high risk to their health as well as for humans who consume their meat and milk (Hudson-edwards et al., 2011; Simate & Ndlovu 2014; Kefeni et al., 2017).

Heavy metals and AMD have the ability to persist in natural ecosystems for an extended period, even for centuries. They have the ability to modify ecosystems permanently which is the case of Rio Tinto in southwestern Spain. Their long-term natural weathering and at least 5,000 years of mining of massive sulfide ore bodies have delivered both natural acid rock drainage (NARD) and AMD to the river, giving it a characteristic red color and high acidity (pH = ~1.7–2) extending some 60 km downstream from the mining area (See figure 6) (Hudson-edwards et al., 2011).

Figure 6. AMD in Río Tinto, Spain (Edwards et al., 2011).

2.3.3. Visual Impact

As it has been mentioned tailings storage facility can cover several square kilometers of land with dams that can reach in the tens of meters, a situation that generates a strong visual impact. For example, the Syncrude Tailings Dam located in Alberta, Canada (See Figure 7). It is an embankment with dimensions about 18 kilometers long and from 40 to 88 meters high. In 2001, it was believed to be the largest earth structure in the world by volume of fill. The Syncrude Tailings Dam is the product of recovery oil sand for decades (Weber, 2012).

The appearance of a proposed infrastructure development is an important issue, especially for the local community. Tailings dams like Syncrude are not exactly the best panoramic view or scenery to contemplate for communities which live close to a mining project. One of the major concerns of the mining industry is its reputation and the achievement of the social license, and these kinds of tailings storage facilities aren't precisely helping to improve this issue. Although the visual impact occasioned for large engineered structures is considered a minor environmental impact, it should be considered as an important concern for the proper development of any project close to a community and should be treated with careful considerations.

Figure 7. Syncrude Tailings Dam, Alberta, Canada (Weber, 2012).

2.3.4. Air and Soil Pollution Through Dust Generation

During the life of a mining project, tailings dams are usually covered with water, and these wet covers prevent wind erosion. In some cases, it prevents sulfide oxidation and acid mine drainage generation. However, the implementation of water cover after mine closure can only be used in regions where climatic conditions will sustain a permanent water cover. In many cases, mine tailings dams are abandoned without proper rehabilitation, a situation that becomes a source of danger for the environment and local communities (Lottermoser, 2011).

Uncovered tailings represent a hazard for local communities due to sever water and wind erosion because of their fine grain size. There have been documented several cases where windblown particles form uncovered tailings have polluted streams, air and soils, creating health problems for employees and the communities settle down close to the tailings dams (Figure 8). Furthermore, weathering and dissolution of tailings dust, which has been deposited in local topsoils can originate the acidification of topsoils and polluted ecosystems by transfer metals and metalloids into local plant species. Tailings disposal areas can cover large amount of land which are likely to become useless for future land use because of the chemical and physical characteristics of the soil (cp. Conesa et al., 2009. In Lottermoser, 2010).

Figure 8. Tailings dam dust generation (Valenzuela et al., 2014).

3. TECHNICAL PARAMETERS OF MINE TAILINGS

According to Bhanbhro (2014), the exploitation and mineral processing method implemented in a mine for recovering the value minerals and the ore type along with the method of reclamation and disposal of mine solid waste define the properties and the long term behavior of mine tailings. For example, depending upon method of deposition and the kind of embankment implemented, each mine tailings layer can have different material and mechanical properties.

Mineral processing methods have as a main objective to change the physical and chemical characteristics of the mine ore due to the dissolution and mobilization of the elements that constitute the ore. The chemical and physical parameters are modified by individual elements and compounds which can be found from the ore deposit to the repository or tailings storage. It has been proved that the composition of tailings changes over the time due to the generation of different chemical reactions that take place into the dams. In addition, mine tailings properties suffer some alterations by biological and physical processes, such as cementation, compaction, mineral dissolution as well as recrystallization and the formation of new elements assisted by microorganisms (cp. Praharaj et al., 2008. In Lottermoser, 2010).

Characteristics such as the grain size of tailings has serious impact on the behavior of mine tailings. They influence the resistance of the tailings to wind and water erosion and the performance and settling characteristics of particles in the tailings dam. Particle shapes are likely to have influence on void ratio, friction angle, and hydraulic conductivity. Physical and chemical properties of solid mine wastes are vital for the safety evaluation and engineering design of tailings dams. These characteristics must be understood in order to recommend new methods which prioritize the utilization and recycling of mine tailings instead the traditional methods for disposal and storage of tailings (Lottermoser, 2011; Bhanbhro, 2014).

This chapter will be focused on some specific physical characteristics or technical parameters that according to research are the most important to be considered for developing new methodologies for reutilization, recycling and reprocessing of mine tailings.

Technical parameters such grain size distribution, specific gravity, Atterberg limits (liquid limit, plastic limit and plasticity index), natural water content, hydraulic conductivity, soil classification, compression characteristics, strength and abrasion of tailings, among other characteristics will be collected and analyzed from different researchers through an extensive bibliography review in order to understand the variety of tailing properties from diverse ore mines worldwide.

Table 3, shows the technical parameters and the type of mine tailings identified through the literature review. Eight cases in different countries were documented: 3 cases about gold tailings dams in Canada and Philippines, 3 cases about copper tailings dams in Iran, Mexico and United Sates, and 1 case regarding iron ore tailings in China as well as 1 case about coal tailings dam in Canada (See table 2).

The collection of data in order to identify the quantity and distribution of all elements and minerals in all scales as well as in space and time in mining wastes worldwide have been for many years one of the most serious limitations concerning reuse and recycling of mine tailings dams (Lottermoser, 2010).

		Copper Tailings	
Case No.	**Location**	**Name of Mine**	**Reference**
1	Iran	Sarcheshmeh Copper Mine	(Shamsai et al., 2007)
2	Mexico	Bahuerachi Copper Mine	(Hu et al., 2017)
3	USA	Kennecott Utah Copper LLC	(Qiu and Sego, 2001)
		Gold Tailings	
1	Canada	Echo Bay Lupin Mine	(Qiu and Sego, 2001)
2	Philippines	Davao Gold Mine	(Adajar, 2012)
3	Philippines	Masbate Gold Mine	(Adajar, 2012)
		Iron Ore Tailings	
1	China	Yuhezai Iron Mine	(Hu et al., 2017)
		Coal Tailings	
1	Canada	Coal Valley Mine	(Qiu and Sego, 2001)

Table 2. Cases identified of mine tailings technical parameters.

Technical Parameters of Mine Tailings Dam

			Mineral									
			Gold			Copper				Iron Ore		Coal
			Case 1	Case 2	Case 3	Case 1	Case 2		Case 3	Case 1		Case 1
							Coarse	Fine		Coarse	Fine	
Technical Parameters	Grain Size Distribution	D10 (mm)	0.005	0.002	0.000	N.R	0.065	0.005	0.016	0.051	0.005	0.001
		D30 (mm)	0.019	0.030	0.008	N.R	0.090	0.028	0.072	0.093	0.012	0.004
		D50 (mm)	0.045	0.085	0.025	N.R	0.120	0.060	0.121	0.120	0.030	0.029
		D60 (mm)	0.054	0.090	0.075	N.R	0.140	0.074	0.154	0.160	0.045	0.060
	Specific Gravity (Gs)		3.17	2.72	2.71	2.79	2.77	2.76	2.75	3.23	3.08	1.94
	Atterberg Limits	Liquid Limit LL (%)	-	24	23	26-39	-	28	-	-	28	40
		Plastic Limit PL (%)	-	0	0	4-12	-	13	-	-	19	16
		Shrinkage Limit (%)	21.6	20	20	-	-	15	24.4	-	9	21.1
	Soil Classification		Silt	Silty Sand	Silty Sand	Sands	Silty sand	Sandy lean clay	Silty sand	Silty sand	Sandy lean clay	Lean Clay
	Natural Water Content W (%)		-	-	-	-	39	67	-	43-54	43	-
	Consolidation Coefficient (Cv) (cm^2/s)		0.004 - 0.025	0.003 - 0.009	0.003 - 0.013	0.005	-	0.044	0.007 - 0.033	-	0.033	0.0005 - 0.005
	Hydraulic Conductivity (K) (cm/s)		$2.7x10^{-5}$ - $6.7x 10^{-5}$	10^{-3} - 10^{-6}	10^{-3} - 10^{-6}	10^{-7} – 10^{-8}	$2.1x10^{-3}$	10^{-5}	$4.5x10^{-5}$ $9.8x 10^{-5}$	$1.0x10^{-4}$	10^{-6}	$4x10^{-7}$– $1.1x 10^{-5}$
	Friction Angle (Φ)		33	32	33	24 - 37	40	38	34	41	32	32

Table 3. Technical parameters of mine tailings dam.

4. GLOBAL SOLID MINE WASTE AND TAILINGS PRODUCTION

The production and consumption of minerals and metals are well documented by mining companies and governments. This information can be found in the annual and financial reports of each mining company. Also, there are many public and private agencies in charge to collect and distributed this data. For example, the U.S. Geological Survey (USGS), the British Geological Survey (BGS), among others. Nevertheless, there is no precisely data available about the global production of mine wastes. Consequently, the following information presented in this chapter about mine waste and tailings production represents approximations and assumptions taken by the literature review and can only be used as an indication of the amount of mine waste produces worldwide.

Waste production varies significantly from nation to nation. The production of mine waste is higher in countries where mining is considered an important economic activity. For example, in Australia, more than 2,100 million tonnes (Mt) of solid waste is produced annually and 80% of this solid waste is generated by the mining sector. At least 1,750 Mt of mine wastes are produced per year, this is by far the biggest producer of liquid, gaseous and solid waste in the country (cp. Connor et al.,1995. In Lottermoser, 2010).

According to the European Commission (EC) (2013), the European Union (EU) produced over 730 million tonnes of mining waste in 2012, where 28.3% of the total waste generated in the EU was attributed to the mining and quarrying industry, second only to construction (34.4%) and ahead of manufacturing (11.0%) and households (8.7%) (Allard et al., 2013). It is estimated that more than 4,700 Mt of mining waste and 1,200 Mt of tailings are stored all over the European Union, especially in countries like Germany, Greece, Finland, Ireland, Portugal, Spain, Sweden, Bulgaria and the United Kingdom. It is due to the importance of the mining industry to their economies (cp. BRGM et al., 2001. In Lottermoser, 2010). For example, just in Portugal, mining and quarrying activities generated 17 Mt in 2001, representing 58% of the total industrial waste (Grangeia et al., 2011). According to the Eurostat statistics (2017), over 3,400 abandoned waste facilities from the extractive industry were registered in 18 national inventories.

In China, coal mining waste has become the primary pollution source. According to the International Energy Agency (IEA) (2017), China has become the largest coal producer and consumer in the world. In 2016, China had produced 3.6 billion tonnes of coal, accounting for over 45% of the total production in the world. The average production of coal mining waste is about 15% of coal production, which varies from 10% to 30% depending on geological and technical conditions. Hence, it is estimated that the annual production of coal mining waste has been about 315 million tonnes just for underground coal mining. There are about 4.5 billion tonnes of coal mining wastes stockpiled in more than 1,700 waste dumps which occupied around 15 thousand hectares of land (Bian et al., 2009). Additionally, there are more than 8,840 state-owned and 260,000 collective and individually own metal mines which account for 70% of the total solid waste generated in the nation, with 30% of the total waste represented by mine tailings. Moreover, more than 4,000 Million tonnes of tailings are stored in tailings dams which covered an additional 2,000 hectares of land annually (cp. Liao et al., 2007. In Lottermoser, 2010). It is estimated that more than 25 billion tonnes of waste tailings have been produced in China, resulting in approximately 12,000 tailings dams around the country (Sun et al., 2018).

In United State, the production of solid mine waste is 10 times bigger than the municipally waste per capita. Around 2,000 million tonnes of solid waste is produced by the mining industry annually (Boger, 2009; Bian et al., 2012). In 2002, the U.S. National Research Council (NRC), estimated that between 70–90 million tonnes of tailings were produced by coal preparation plants in the United States. Another example, is the production of phosphate in Florida, which produces more than 90,000 tonnes per day of waste clay on a dry basis (Boger, 2009). In general, mine wastes represent the greatest proportion of waste produced by industrial activity. In fact, some authors agree that the mineral industry is the largest producer of waste in the world (Boger, 2009).

There is no official and accurate data available about the global production of mine wastes. Consequently, an estimation of the annual production of solid mine waste worldwide has to be calculated based on the fallowing assumptions. In 2016, approximately 3,200 tonnes of gold were produced worldwide, assuming an average gold grade of 2 parts per million (ppm), the production of this amount of gold generated about 1,600 Mt of solid waste. Moreover, in this year more than 75 Mt of metals (Cu, Cr, Hg, Ni, Pb, Co, Be, As, Ta, Zn, V, among others) were produced (See Table 4), assuming that the average ore grade of these metals deposits was 0.5%, mining, processing and extraction of these ores generated at least 15,000 Mt of solid waste. Furthermore, in the same year around 2,300 Mt of iron ore, 280 Mt of bauxite, and 7,100 Mt of coal and more than 3,500 Mt of industrial minerals were consumed globally. According to Lottermoser (2010), for every tonne of these ores consumed, there would have been at least the same amount of solid waste generate. Such calculations indicate that approximately 30 billion tonnes of solid mine wastes are produced annually worldwide and more than 7 billion of these tonnes are considered mine tailings (See Table 5). It means that mine tailings represent at least 25% of the total solid mine waste generated worldwide (Lottermoser, 2011; Adiansyah et al., 2015; Edraki et al., 2014).

The production of mine waste may even double in 20 years (cp. Connor et al.,1995. In Lottermoser, 2010). Consequently, to discover a solution for proper management of mine tailings, which instead of storing them promotes new methodologies for their reutilization, recycling and reprocessing is indispensable.

Mineral or Product	Production 2016	Mineral or product	Production 2016
Arsenic	37,000 t	Tin	306,000 t
Beryllium	220 t	Vanadium	74,000 t
Cobalt	128,000 t	Tungsten	88,700 t
Chromium	34 Mt	Zinc	12.3 Mt
Copper	20.7 Mt	Tantalum	1,600 t
Mercury	4,000 t	Gold	3,200 t
Nickel	2 Mt	Iron Ore	2,350 Mt
Lead	4.7 Mt	Bauxite	289 Mt
Antimony	150,000 t	Coal	7,143 Mt

Table 4. World production of selected mineral commodities in metric tons in 2016 (Mt: Million tonnes) (BGS, 2016; BFNT, 2018; USGS, 2017).

Mineral	Total production 2016	Assumption	Solid Waste production
Gold (Au)	3,200 t	2 ppm (a)	1,600 Mt
Iron ore, Bauxite, Coal and Industrial Minerals	13,282 Mt	1:1 (b)	13,282 Mt
Cu, Cr, Hg, Ni, Pb, Co, Be, As, Ta, Zn, V.	75 Mt	0,5 % (c)	15,000 Mt
Total production of mining waste			**29,882 Mt**
Total production of mine tailings			**7,470 Mt (d)**

Table 5. Calculation of global production of solid mine waste and mine tailings in 2016.

a. Assuming an average gold grade of 2 ppm.
b. Assuming that for each tonne of these ores consumed, there would have been at least the same amount of solid waste generate.
c. Assuming that the average ore grade of these metals deposit was 0.5%.
d. Assuming that between 20 – 25% of solid mine waste generate is mine tailings.

4.1. Mining Waste Production by Mineral

Due to the significantly growing of global standards of living, the improvement of the economies of poor countries and the accelerate increasing of the world population, the production and consumption of minerals and metals has consequently increased (See Figure 9). According to Vidal et al (2017), the exponential growth of all indicators of human activity and prosperity have had as a consequence the global acceleration of industrialization during the 20th century. Specially, in the consumption of specific mineral resources, such as gravel, sand, cement, raw materials and industrial minerals which are mainly due to the expansion and development of urban areas that imply to cover the basic needs that arise like transportation, energy and production of different goods. Indeed, the authors agree that humanity is consuming natural resources at the highest level which never been seen before. For example, Per-capita levels of resource consumption are at their highest level in history, and raw material extraction is extraordinary which a total amount of 70 billion tonnes per year (Wiedmann et al., 2015; Vidal et al., 2017).

According to Bleischwitz and Nechifor (2016), the annual consumption of copper and aluminum stabilizes when the gross domestic product (GDP) per capita reaches US$20,000 – $25,000. While for structural raw materials stabilize when the GDP per capita reaches about US$15,000 – $20,000 for steel and concrete consumption. Many countries with large population and developing economics, such as China, India, Pakistan, Indonesia, Africa and some Latin American countries currently have GDP/capita of less than US$15,000. Then, it is possible to state that the industrialization of these countries will be inevitable and it be associated with an increase in the consumption of raw materials. A clear example of this situation is the fast industrialization of China since 1990s with has implied to reach the highest level of global consumption of concrete (6%/year) and steel (5%/year) as well as other minerals like Mn (6%/year), Cu (3%/year), Ni (5%/year), Cr (5%/year), and Zn (4%/year) (See Figure 10 A and 10 B) (Vidal et al., 2017; Nishiyama, 2005).

The problematic with mining wastes in particular the issue of mine tailings could be seen as an opportunity to create a valuable market that could deal with this problem by recycling, reusing or reprocessing mining tailings (Carmo et al., 2017; BBC, 2019) .

Lottermoser (2011), says that:

"Yesterday's waste can be today's resources. What may be a waste of some can be a very useful resource to others, either now or in the future."? (Lottermoser 2011, p. 407).

Mine tailings dams today can be seen as the reserves for tomorrow's recycling. They can still contain minerals and metals that in the past had not valuable, but may in the present, they do, principally because development of new technology that allows their extraction and processing, or maybe because a new market or application have been identified for their utilization (see Table 6, in chapter 5). This is why the mining waste market is getting more attention and becoming much more important for some mining companies and organizations which support research that has as a major objective to identify new methods or create new technologies which allow increased resource recovery that at the same time address environmental concerns related with the management of tailings (Lottermoser, 2011).

Mining waste production could be classified using different criteria. For example, by mining method (surface or underground mining), by metal or mineral, by waste type or by region (Figure 11). However, for the purpose of this research just the Scopus of the mining waste production by metal or mineral will be addressed. The ores considered for this study of the mining waste production have been limited to copper, gold, iron ore, bauxite and coal. The key reason for this is because these minerals are some of the main raw materials which the highest demand and production in the global market (See Table 4), and subsequently they are the biggest producers of mine wastes worldwide (See Table 5).

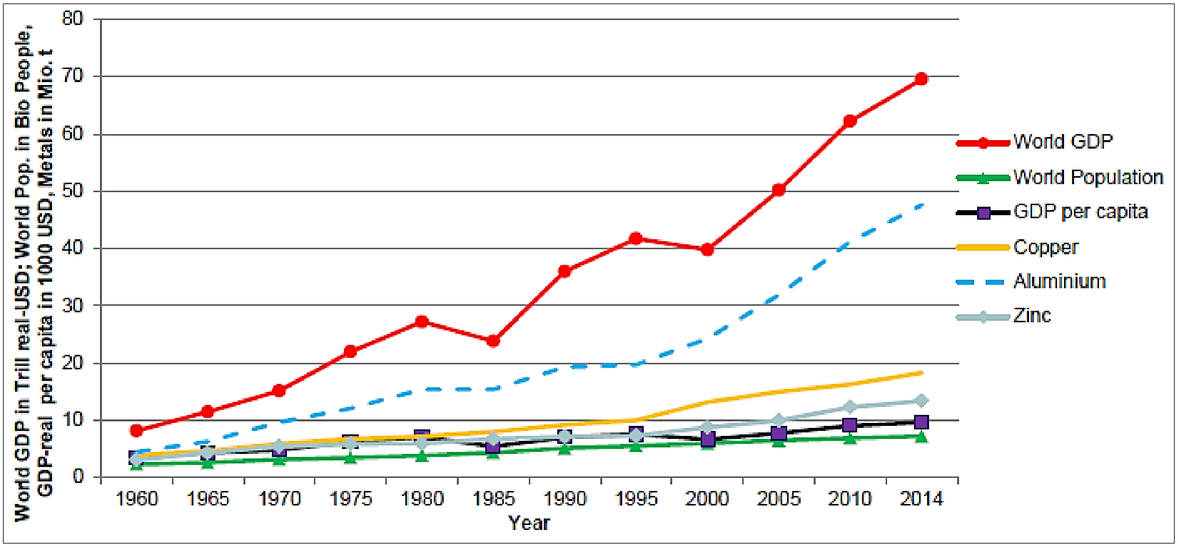

Figure 9. World Development 1960 – 2014 (Professor Drnek, Montanuniversitaet, 2017).

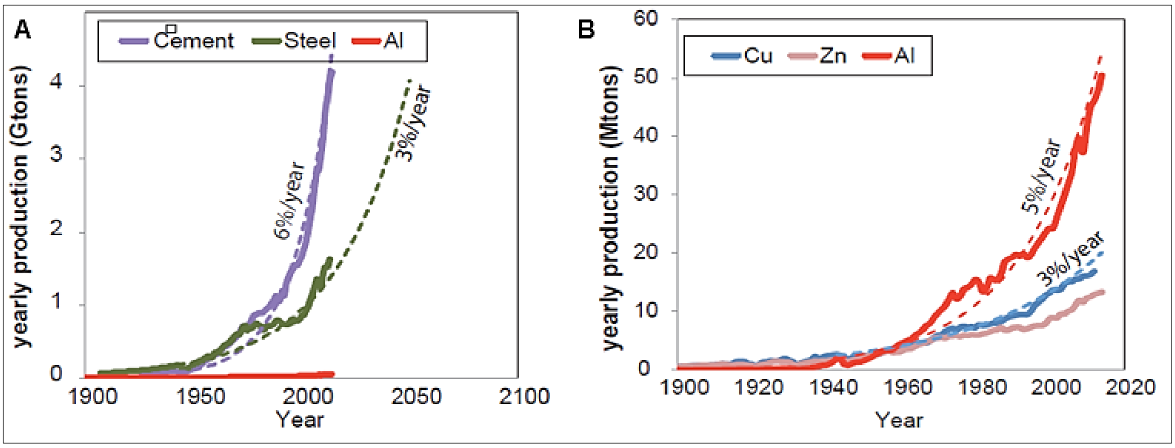

Figure 10. (A) Yearly production, between 1900 and 2015 of cement, steel and Al. (B) Yearly production, between 1900 and 2015 of Cu, Zn and Al, in China (Vidal et al., 2017).

Figure 11. Market classification of solid mine waste production (M&M, 2016).

4.1.1. Copper Mining Waste Production

Copper (Cu) is considered one of the most used minerals worldwide. Copper is essential for many economic sectors, including infrastructure, communication wiring, plumbing, electrical and electronic equipment, transportation, and consumer goods, among others. The demand of copper is not expected to decrease over the next decades, instead it is expected to increase suggestibility during this century. In fact, the total copper mining production in the last 10 years has increased by more than 4 million metric tons (Figure 12) (Kuipers et al., 2018; Elshkaki et al., 2016; Nishiyama, 2005; BGS, 2016).

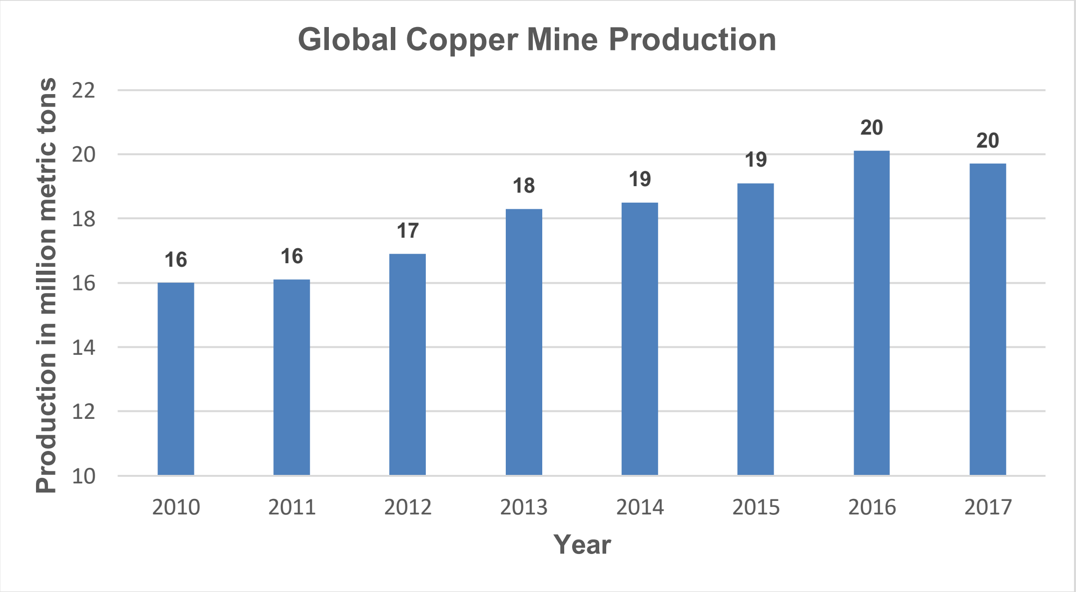

Figure 12. Global copper mine production from 2010 - 2017, in million metric tons (BGS, 2019).

In 2017, the ten leading countries in world copper production were Chile, Peru, China, the United States, Australia, the Democratic Republic of the Congo, Zambia, Mexico, Indonesia and Canada, respectively. These ten countries represent almost the 80% of the total global copper production. Chile is the world's leading copper producer by far; with an average production of 5.33 million metric tons of copper which represented a share of 27% of the worldwide copper production in 2017. The second place was occupied by Peru; with an estimated copper mine production of 2.39 million metric tons for the same year. The world's third-largest copper producer from mines was China with a production of 1.86 million metric tons of copper in 2017, which is over three times less than Chile's production (Figure 13) (Statista, 2018; USGS, 2017).

Chile hosts six of the ten largest copper mines in the world, while the remaining four are located in Peru, Mexico and Indonesia. Three of the world's ten largest copper mines based on capacity are located in Chile. At the top of the list is the Escondida mine, located in the Atacama Desert in Chile's Antofagasta Region. In 2018, It produced around 1.37 million metric tons of copper, which is approximately twice the capacity of the world's second-largest copper mine: Grasberg mine located in Indonesia (Statista, 2018; USGS, 2017).

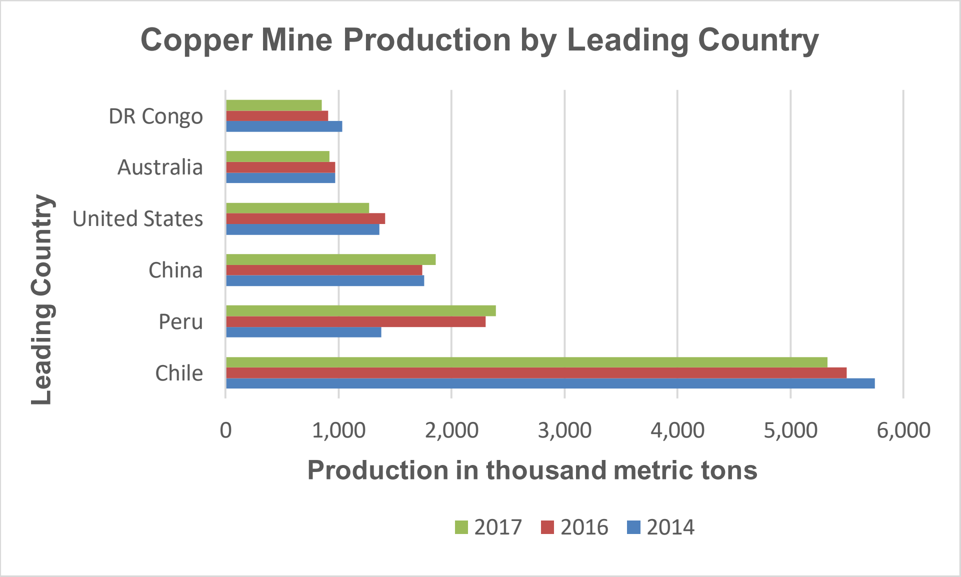

Figure 13. Copper mine production by leading country from 2014 - 2017, in thousand metric tons (USGS, 2019).

Figure 14 presents the leading copper mine companies worldwide in 2017. It shows the world's 10 biggest copper producers which accounted for almost 10 million metric tons. The top four companies (Codelco, Freeport-McMoRan, BHP Billiton and Glencore) accounted for more than 60% of that total. In 2017, Codelco produced more than 1,800 thousand metric tons of refined copper, approximately 11 percent of world's total production (Bell, 2018; USGS, 2019).

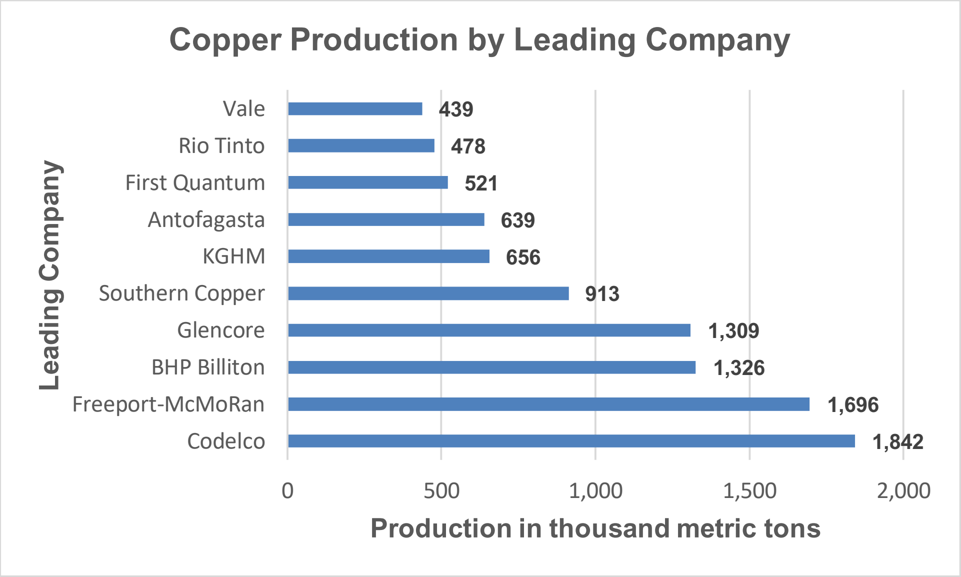

Figure 14. Copper mine production by leading company in 2017, in thousand metric tons (USGS, 2019).

According to Lottermoser (2010), the average ore grade of copper ore deposits is about 0.5%. And the global mining production of copper in 2017 was about 20 million metric tons (USGS, 2017). Then, it can be calculated that the production of solid mining waste in this year was around 4 billion metric tons. Furthermore, assuming the same parameters, it is reasonable to calculate the global production of mining solid waste generate by the copper mining industry for the last decade (Figure 15). Figure 15 shows that the production of copper mine solid waste has had a significant increase (almost 1 billion metric tons) from 2010, where the production was about 3 billion metric tons to compare with almost 4 billion metric tons of Cu solid waste generated in 2017. Furthermore, according to Lottermoser (2010), tailings correspond to 20 – 25% of the total mining solid waste generated. Then, the total production of copper mine tailings can be estimated. The production of the last decade was calculated following the previous assumption (See Figure 16).

According to the National Service of Geology and Mining of Chile ("SERNAGEOMIN", for its Spanish acronym) (2018), there are more than 23 thousand million metric tons of copper tailings spread to all over the country. Chile currently produces 1.4 million tonnes of tailings per day as a result of fine copper production, every year there is an accumulation of more than 50 Mt of copper mining tailings, and the statistics show that the production of these will keep growing at least during the next two decades due to the ore grades have been decreasing in more than 46% in Chile and in 23% for the rest of the world. In 1990s, the average copper ore grade in Chile used to be 1,6%, but nowadays is around 0,87% and in some special cases the ore grade is even less than 0,3% (SERNAGEOMIN, 2016; La Tercera, 2015; SERNAGEOMIN, 2018). Most of the countries do not have a specialize Tailings Agency as Chile has. Then, to obtain accurate data about the amount of tailings and its rate of production is complicated. However, taking Lottermoser assumptions an approximation can be calculated. According to above, the annual copper tailings production by leading countries can be estimated and it is illustrated by Figure 17.

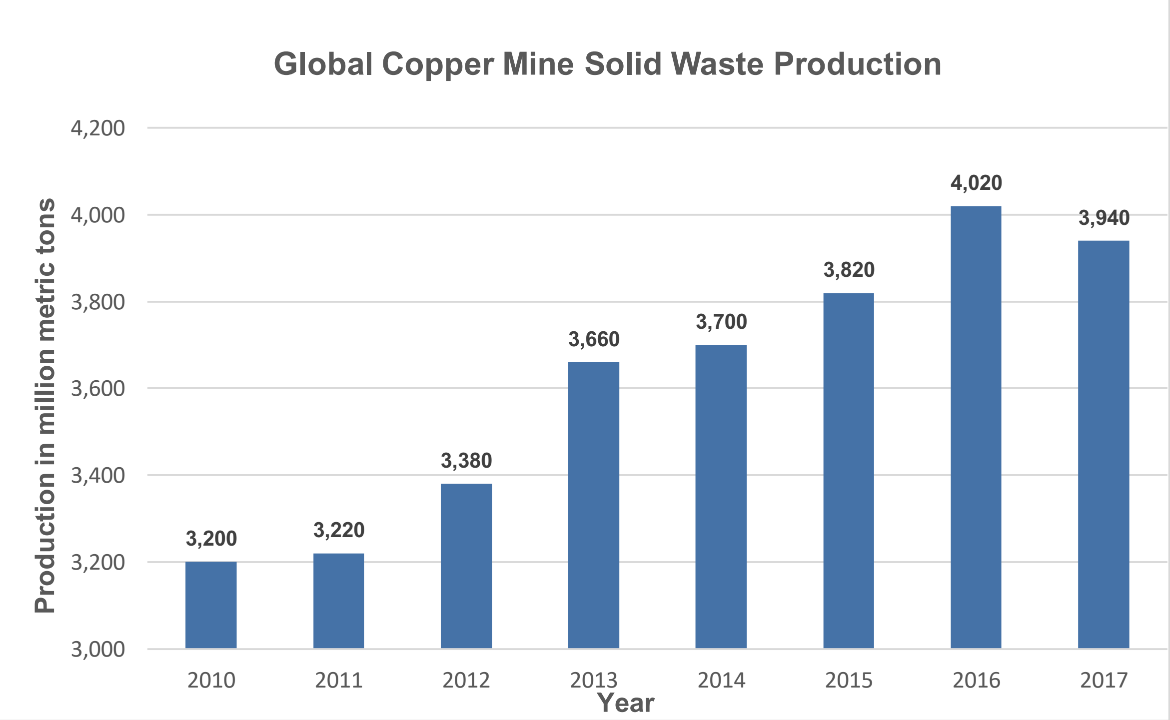

Figure 15. Global copper solid waste production from 2010 – 2017, in million metric tons.

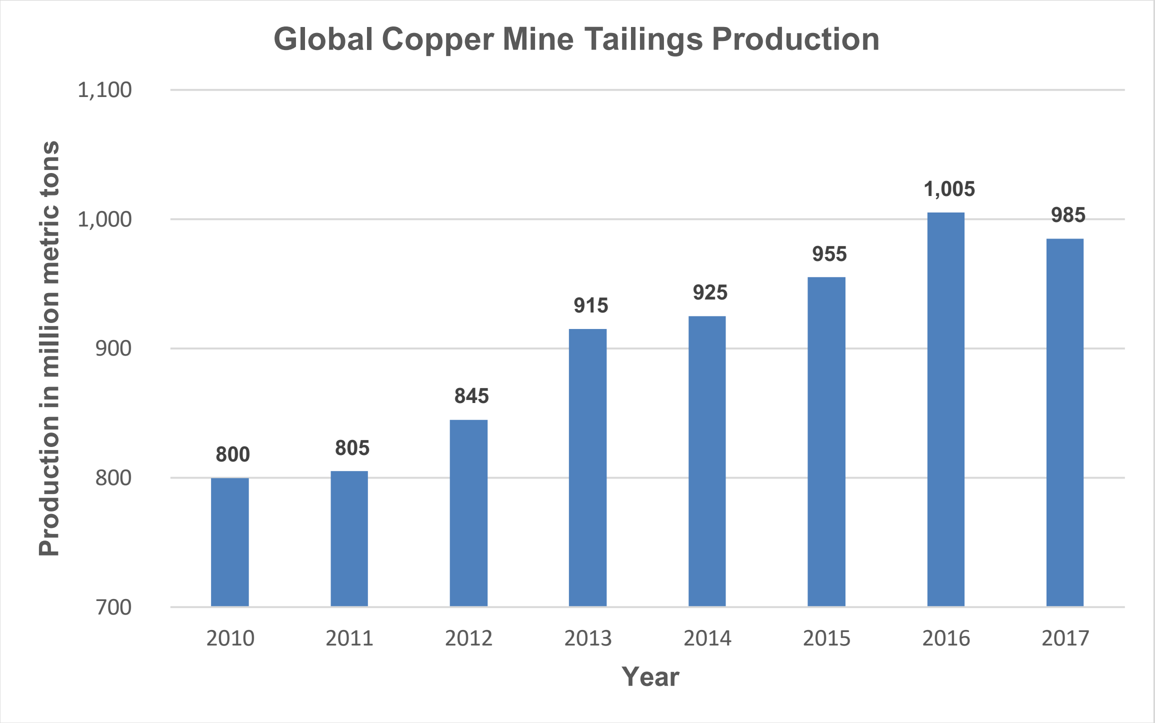

Figure 16. Global copper mine tailings production from 2010 – 2017, in million metric tons.

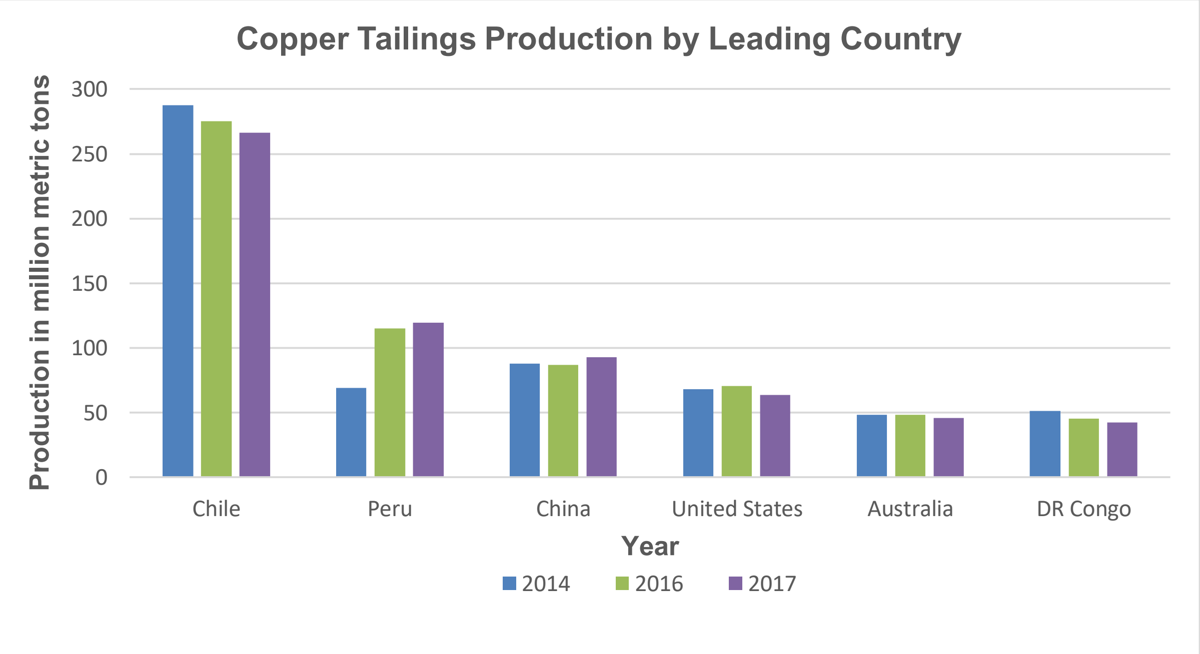

Figure 17. Copper mine tailings production by leading country from 2014 – 2017, in million metric tons.

4.1.2. Gold Mining Waste Production

Research and technological advances in milling and refining processes in the mining industry during the last decades have improved the economic value of most mineral deposits, even for abandoned deposits. In the past, gold recovery efficiencies were in the ranges of 35 – 60%, depending on the extraction techniques and ore properties. In nowadays, gold recovery efficiencies are in the ranges of 92 – 97%. This is why some mine tailings dams that in the past were considered waste, in recent times have been mined and processed (Oppong et al., 2018). In order to have an idea about the potential quantities and location of gold mine tailings which could have opportunities to be reused or reprocessed is necessary to characterize the production of gold mining wastes, to have an estimation about the production of gold mine waste and more precisely gold mine tailings in the last years as well as to know the main producers.

The production of gold augmented in almost 600 metric tons from 2010 to 2017. Figure 18 illustrates the world mine production of gold from 2010 to 2017. Furthermore, China, Australia, Russia, and the United States are some of the largest producers of gold in the world (See Figure 19). Figure 20 indicates the production output of the world's leading gold companies in 2017. In this year, Barrick Gold produced more than 5 million ounces of gold, following for Newmont Mining with a little more of 5 and AngloGold Ashanti with 3,7 million ounces of gold, respectively (BGS, 2019; USGS, 2019).

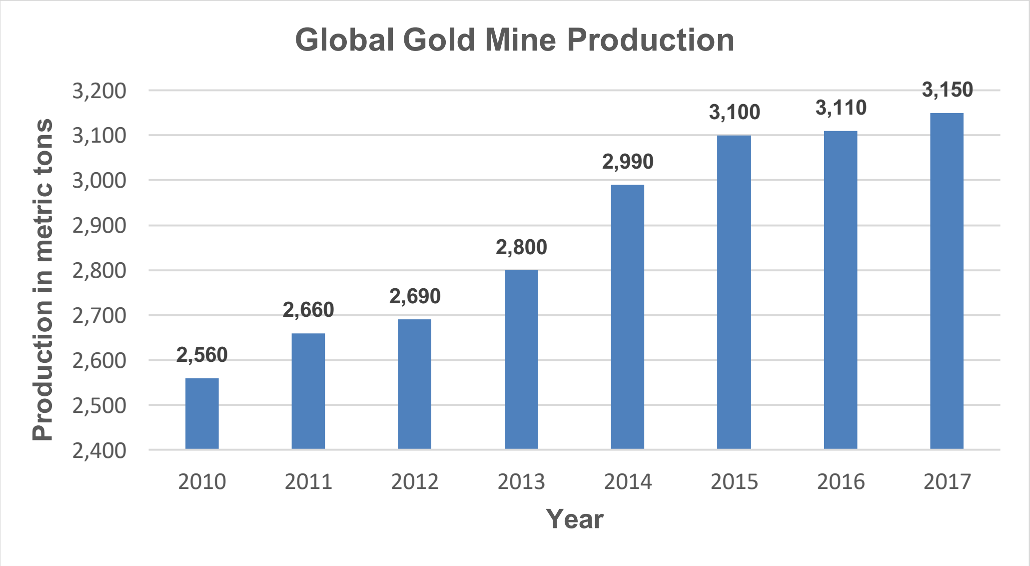

Figure 18. Global gold production from 2010 - 2017, in metric tons (USGS, 2019).

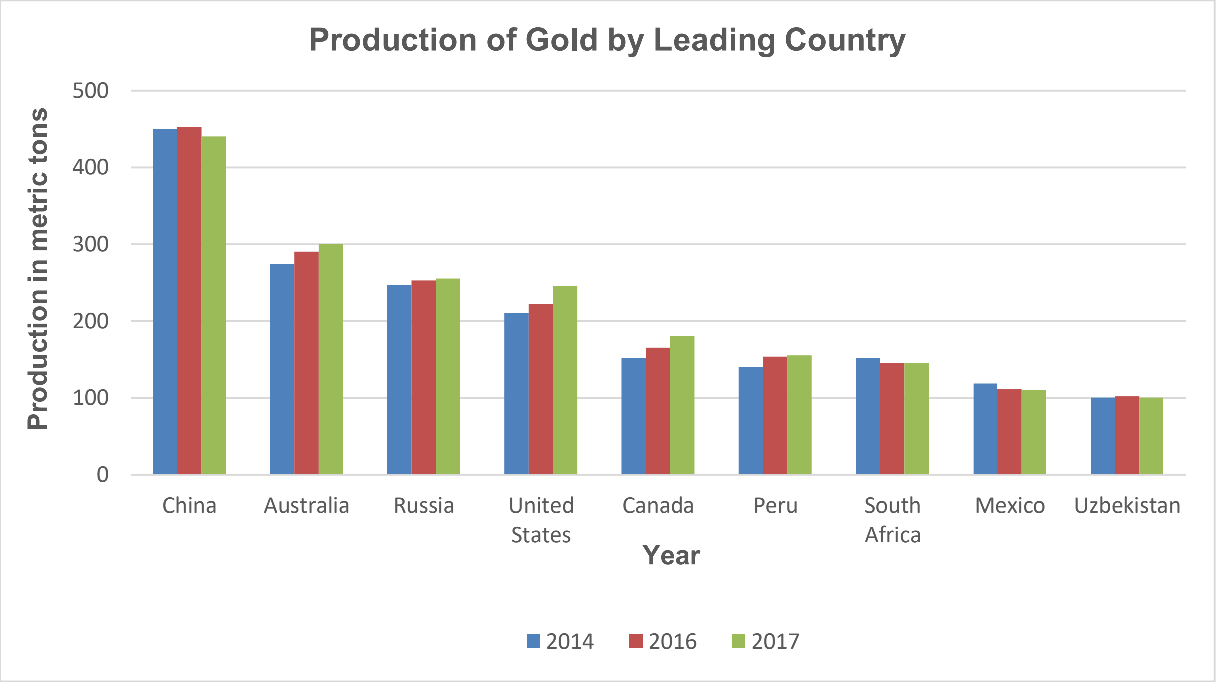

Figure 19. Gold production by leading country from 2014 – 2017, in metric tons (USGS, 2017).

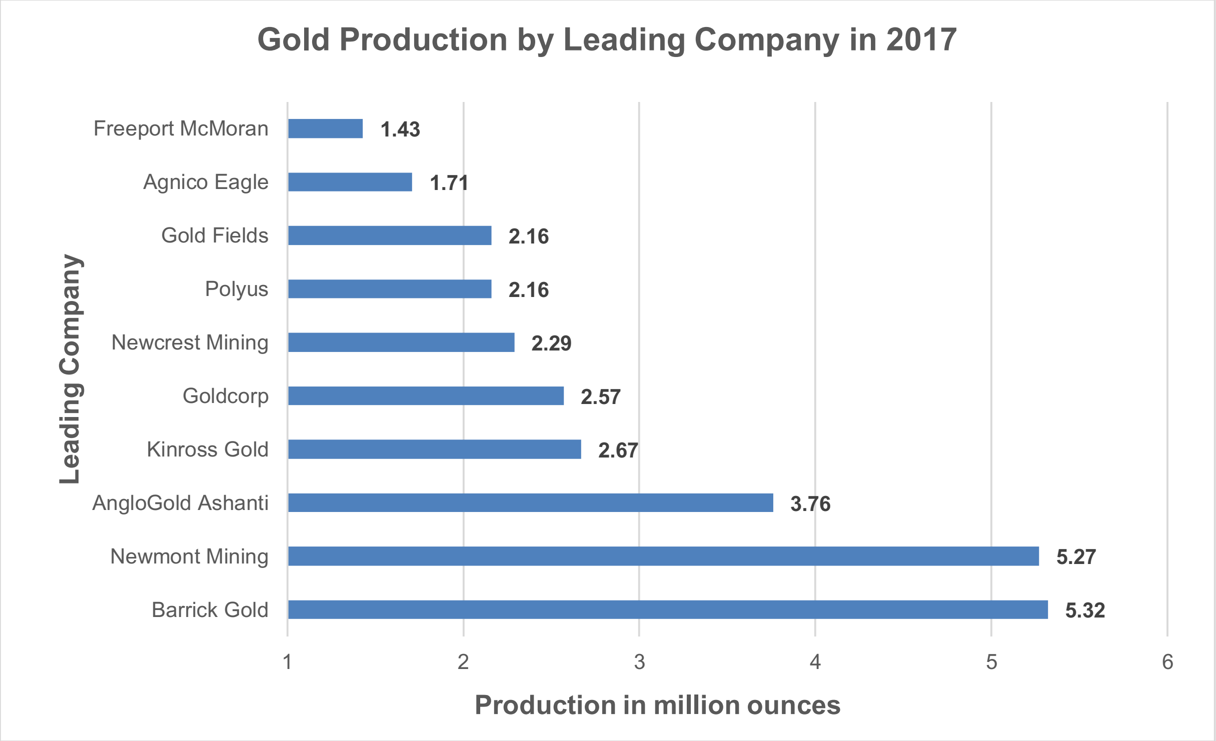

Figure 20. Gold production by leading mining company in 2017, in million ounces (USGS, 2017).

As well that in most of the metal and mining industry, there is not accurate available data about the production of mining waste generate by the extraction and processing of gold. However, there is detailed information about the production of gold, and estimation of gold mine wastes and tailings generated by each metric ton of gold produced can be calculated. According to some authors, it is expected that only 0.00001 percent of the gold ore is actually refined into gold and everything else is considered waste (Lottermoser, 2010). Others state that the average gold ore grade is about 2 parts per million (ppm). As reported by Earthworks and Oxfam America (2004), for every ounce of gold around 79 tonnes of waste are produced. Taking into account the previous statements, it is possible to estimate the total solid mining gold waste and tailings production.

Figure 21 shows that the production of global gold solid mine wastes in 2017, was about 1.5 billion metric tons, and the worldwide gold mining tailings generation for the same year was about 380 million metric tons. The above considering an average gold ore grade of 2 ppm and assuming that 25% of the total solid mine waste generates is mining tailings (See Figure 22). Additionally, assuming the previous statement, the annual gold tailing production by leading countries can be estimated and it is illustrated by Figure 23.

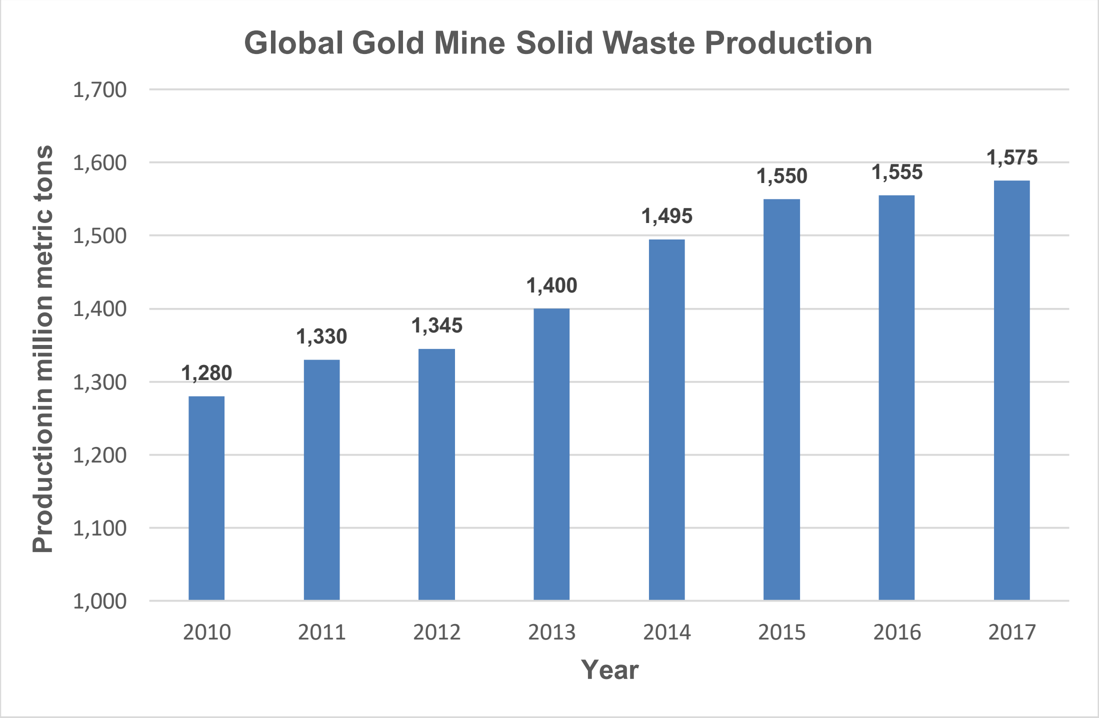

Figure 21. Global gold production of mining solid waste from 2010 – 2017, in million metric tons.

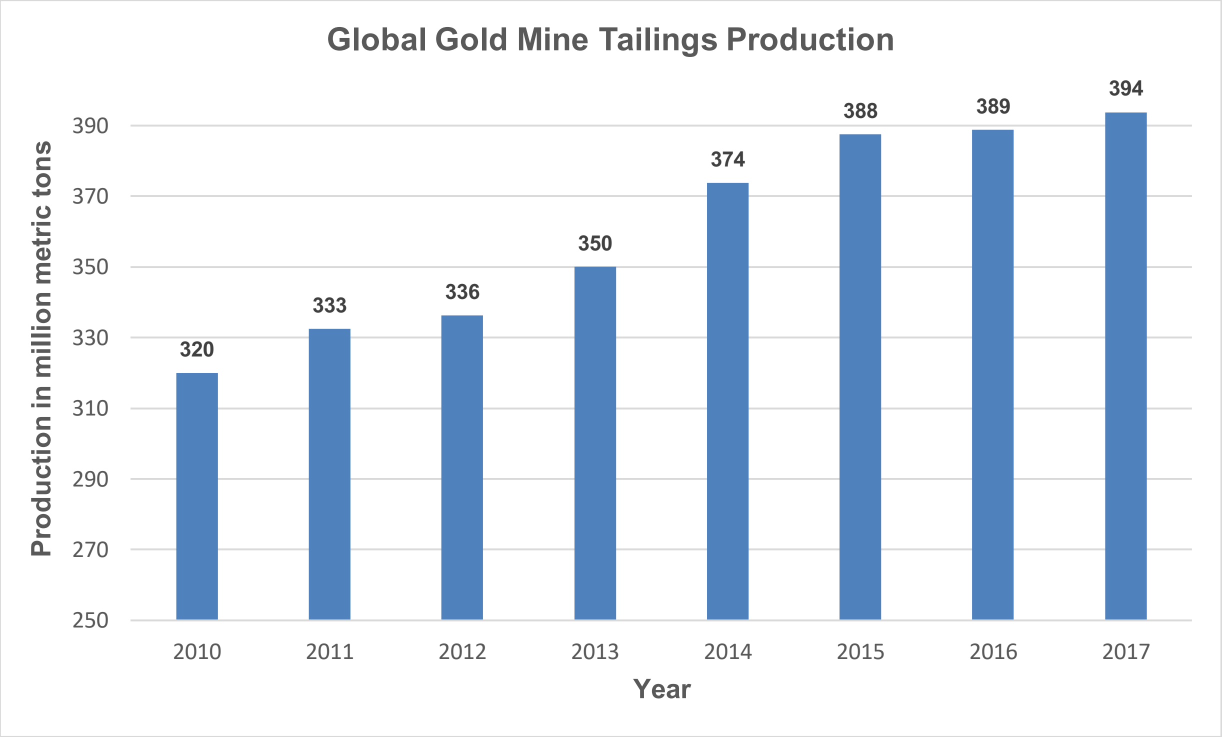

Figure 22. Global gold mine tailings production from 2010 – 2017, in million metric tons.

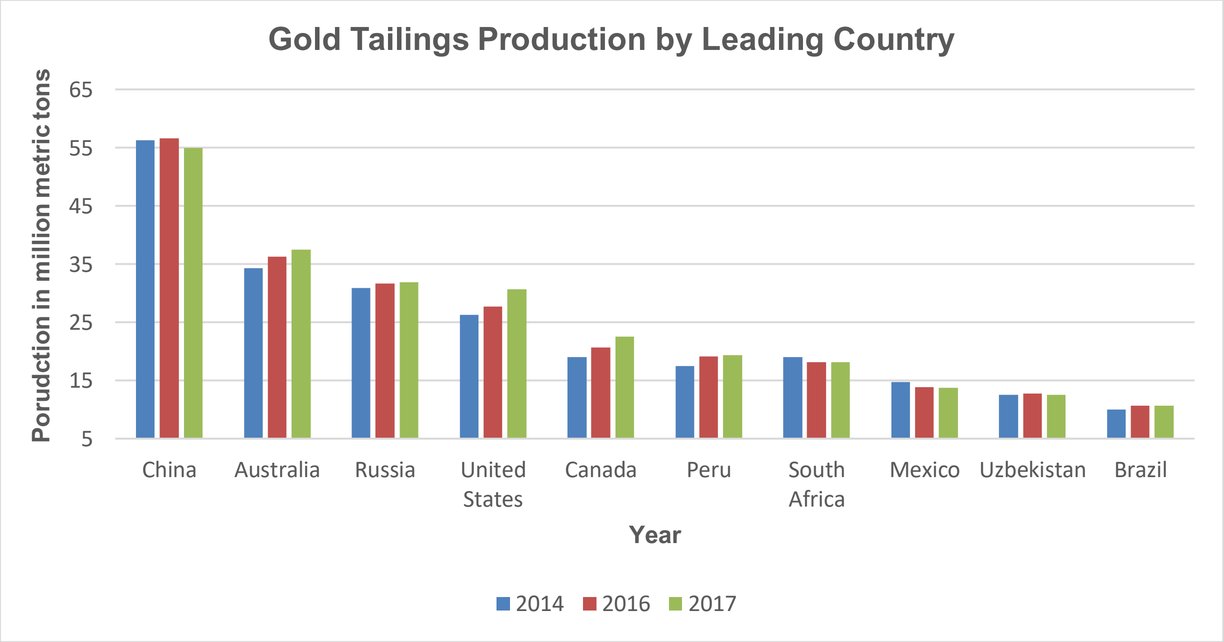

Figure 23. Gold mine tailings production by leading country from 2014 – 2017, in million metric tons.

4.1.3. Iron Ore Mining Waste Production

Iron ore is the most commonly used metal worldwide. It is primarily used by the automotive industry, construction, machinery, engineering, and often as the main component in the steel industry. Consequently, the iron ore mining industry produced billions of solid waste annually. Tailings generated by the processing of iron ore have become of vital importance in the environmental and economic scene since a continuous increase of hazardous events generated by iron steel industry. For example, the resent dam failure in Brumadinho, Brazil, on February 15, 2019, which killed more than 200 people. Just in China, there is an estimation of almost 60 billion tonnes of tailings discarded as waste spread around the country, and the generation of iron ore tailings is assessed to be one third of the total tailings. It means that there are more than 20 Billion tonnes of iron ore mine tailings accumulated. According to many authors, the annual emission of iron ore tailings in China is about 130 million tonnes (BBC, 2019; Carmo et al., 2017; Barros et al., 2018; Li et al., 2010; Da Silva et al., 2014).

Reuse and recycling of iron ore tailings have become an opportunity for dealing with its problems. In nowadays, there are different ways to reuse of iron ore tailings such recycling of Co, Fe, Ni and Cu. Also, for the production of cement clinker, paints, glass ceramic, among others (Li et al., 2010a). The information about the generation of mining waste due to the extraction and processing of iron ore can be of great help to characterize this potential market and to consider any opportunity that promote better management of iron ore tailings.

In 2017, the global mine production of iron ore reaches more than 2,400 million metric tons (See Figure 24). Western Australia is the largest iron ore producer and exporter in the world with 880 Mt of iron ore mined in 2017, accounting for 38% of global production while Brazil is the second largest iron ore producer and exporter in the world with a production of 440 Mt, accounting for 17% of global production in the same year. China occupies the third position with a production around 350 Mt of iron ore. China's ore production values are not based on usable ore (whereas all other countries are). Instead, China's values are based primarily on the production of raw ore (See Figure 25) (USGS, 2017).

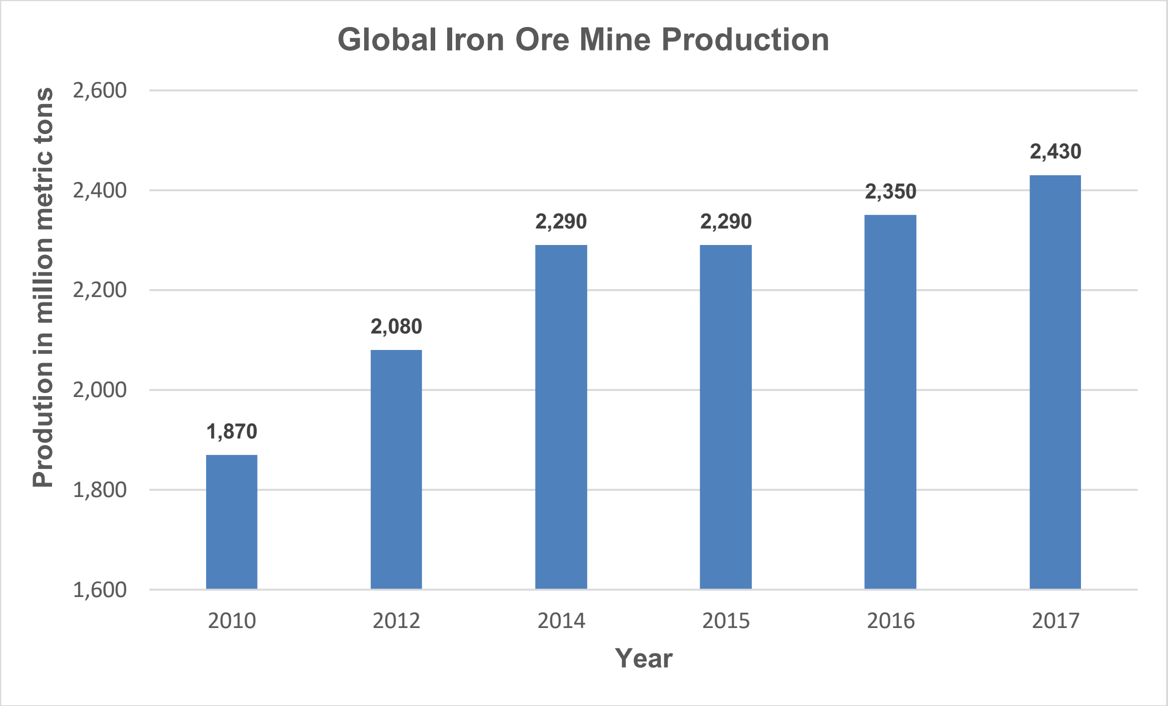

Figure 24. Global production of iron ore from 2010 – 2017, in million metric tons (USGS, 2017).

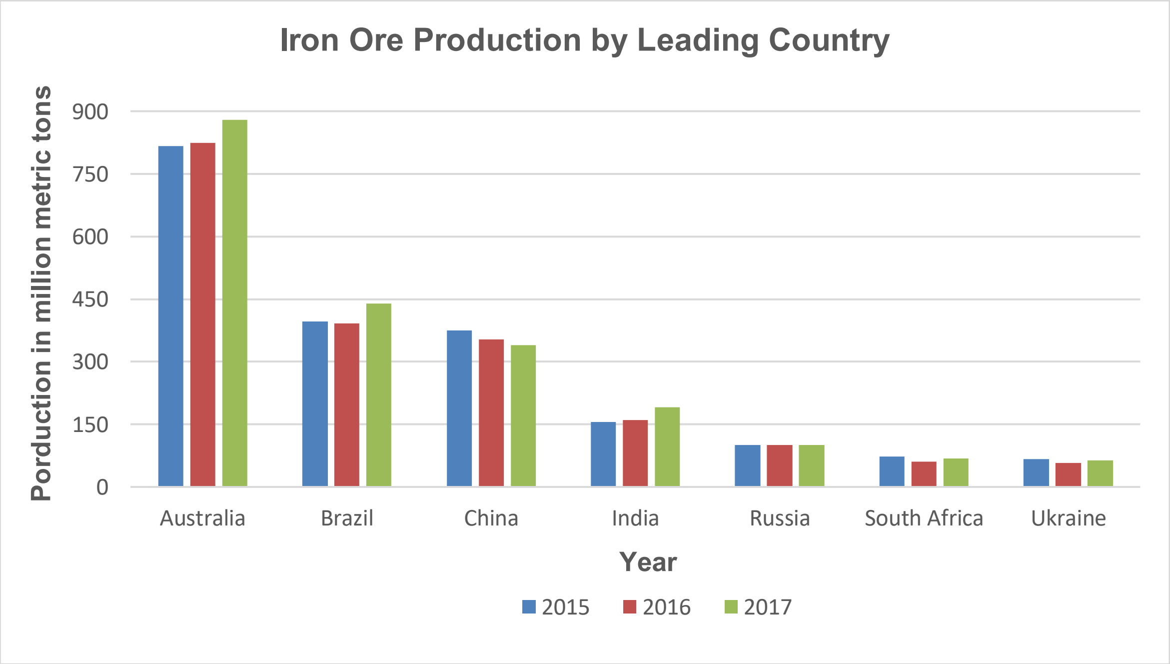

Figure 25. Iron ore production by leading country from 2015 – 2017, in million metric tons (USGS, 2017).

As the same case of copper and gold, the consumption of iron ore is well documented and reported by mining companies and for different private and public organizations. Nevertheless, there is no data available about the worldwide production of iron ore mine wastes. In fact, The Australian Institute of Research states that there are a few reliable statistics on the state of Australia's mines and even harder to get data on mines that had suspended operations (ABCN, 2017). Consequently, an estimation of the annual production of iron ore mine wastes globally and by leading country has to be based on several assumptions. For example, some authors estimated that for each tonne of beneficiated iron ore, 400 kg of tailings are produced (Dauce et al., 2018). Others state that 1 tonne of iron ore concentrate discharges between 2,5 - 3 tonnes of iron ore tailings (Li et al., 2010a). According to Lottermoser (2010), for every tonne of iron ore consumed, there would be at least the same amount of solid waste generated.

Taken the previous hypothesis suggested by Lottermoser (2010), it is possible to state that in 2017, the production of iron solid mining waste was almost 2,500 Mt (Figure 26). Furthermore, the production of iron mine tailings was about 600 million metric tons for the same year (Figure 27). Additionally, as it is obvious to suppose the major producer of mine waste and tailings were Australia, Brazil and China (Figure 28) which are the leading countries of iron ore production.

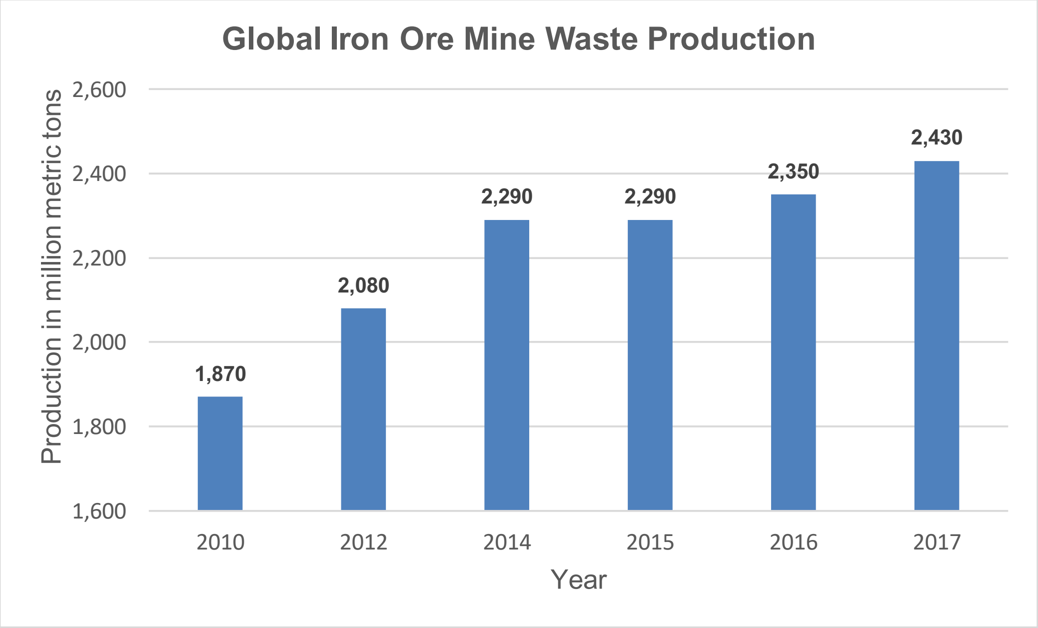

Figure 26. Global iron ore mine waste production from 2010 – 2017, in million metric tons.

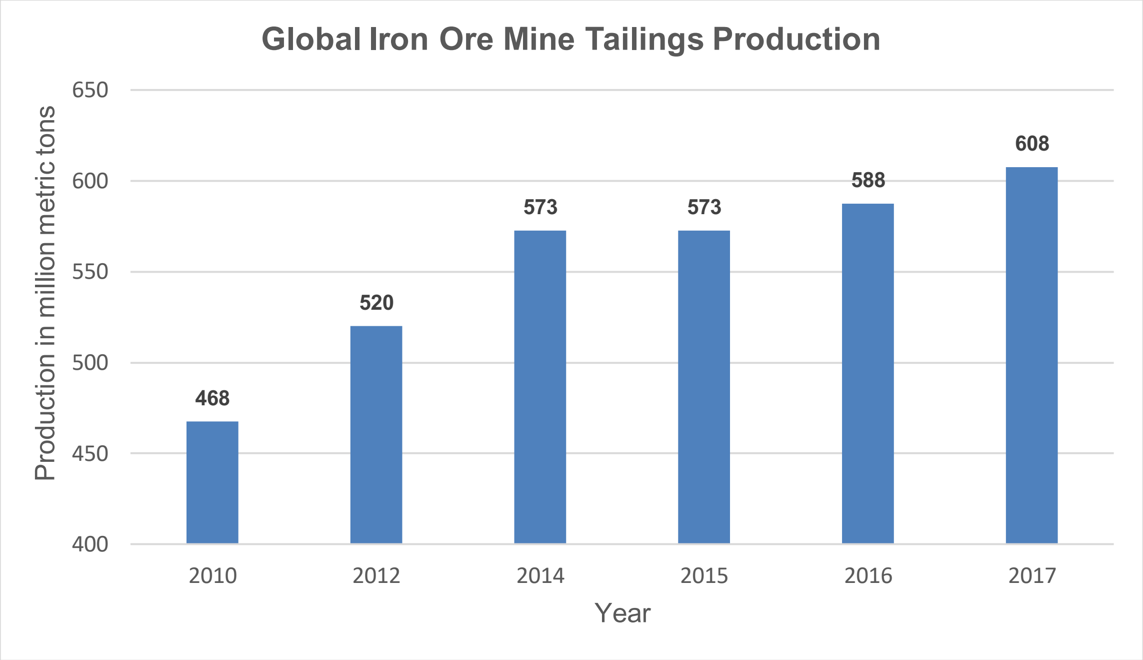

Figure 27. Global iron ore mine tailings production from 2010 – 2017, in million metric tons.

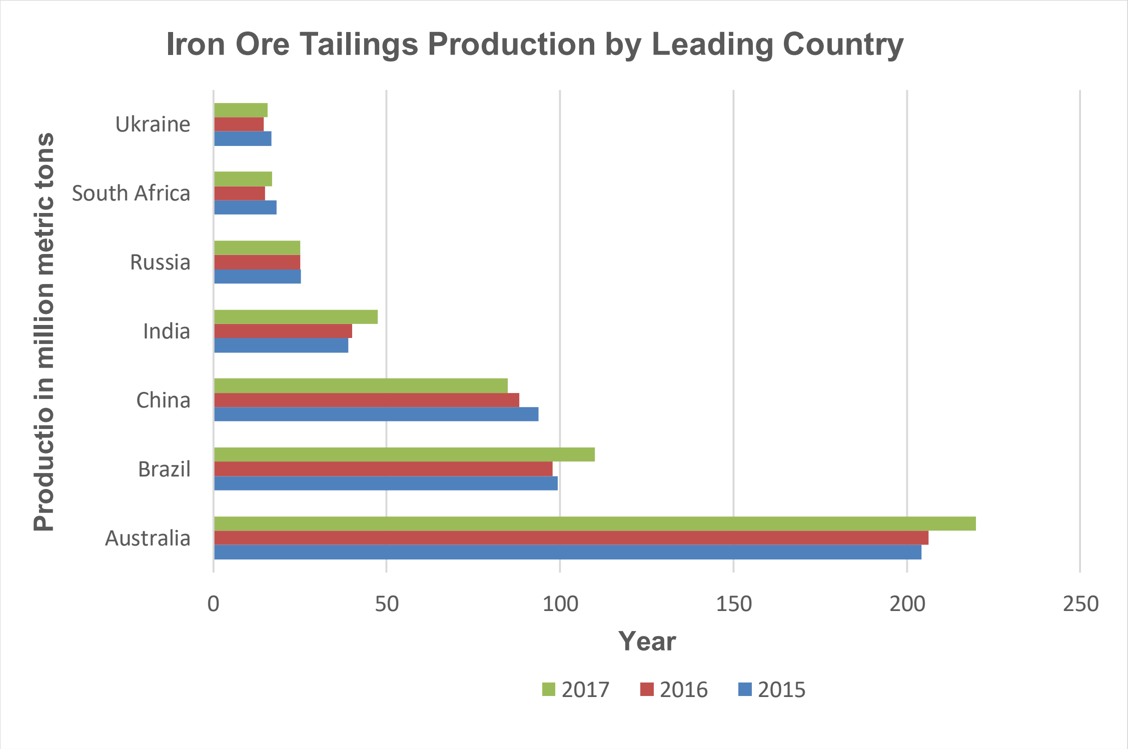

Figure 28. Iron ore mine tailings production by leading country from 2015 – 2017, in million metric tons.

4.1.4. Bauxite Mining Waste Production

Bauxite is the primary ore of aluminum. Most of the aluminum that has ever been produced has been mined from bauxite deposits. The particular properties of aluminum like its high resistivity to corrosion have made this mineral a widely used material for many applications, such as construction, transportation, aerospace industry, packaging and marine construction, among other (Freiria, 2013). However, the production of alumina can also lead to serious environmental problems, mainly due to the bauxite residues or also known as red mud which is the waste product generated during alumina production from bauxite by the Bayer process. Red mud is composed mainly of alumina, iron and titanium minerals. Also by calcium and sodium aluminum hydro silicates. The main problems are associated with its high alkalinity which is harmful to water, land and air (Liu et al., 2009; Marin et al., 2018).

Proper management of bauxite residues is of increasing environmental concern. There is an estimation of 2.7 billion metric tons of red mud being accumulated in tailings dams during 120 years of bauxite extraction. This volume is currently increasing by approximately 120 - 150 million tonnes annually (Klauber et al., 2011; Power et al, 2011; Liu et al., 2014; Marin et al., 2018; Liu et al., 2009).

According to Liu et al (2014), bauxite production growth will remain high over the coming years because of the opening of new projects in Australia. Also, it is expected that Indonesia expands exports as well as India increase its production. In 2017, the global production of bauxite reached to almost 310 million metric tons, 40 more million than in 2016 (Figure 29). Australia, China and Brazil are the three major producers of bauxite in the world, generating more than 80, 60 and 30 million metric tons of bauxite, respectively, in 2017 (See Figure 30). In 2017, China had a total smelter production of some 32 million metric tons of aluminum (See Figure 31). In fact, China is the largest producer of both alumina and red mud in the world (USGS, 2017; BGS, 2016; Liu et al., 2014).

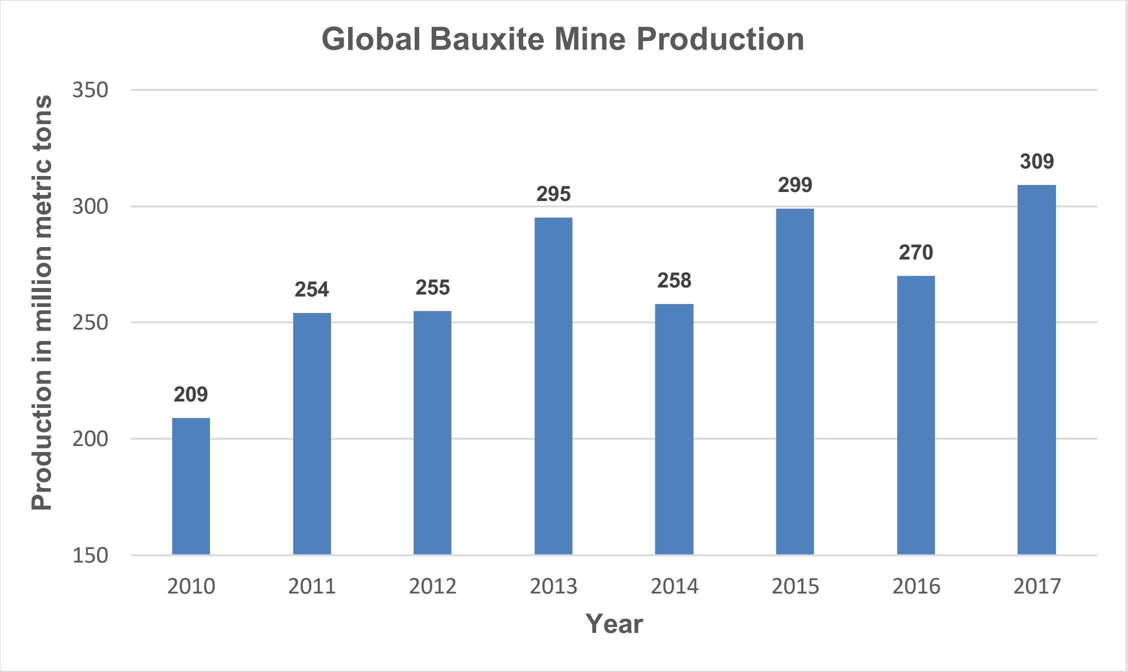

Figure 29. Global Bauxite mine production from 2010 – 2017, in million metric tons (USGS, 2017).

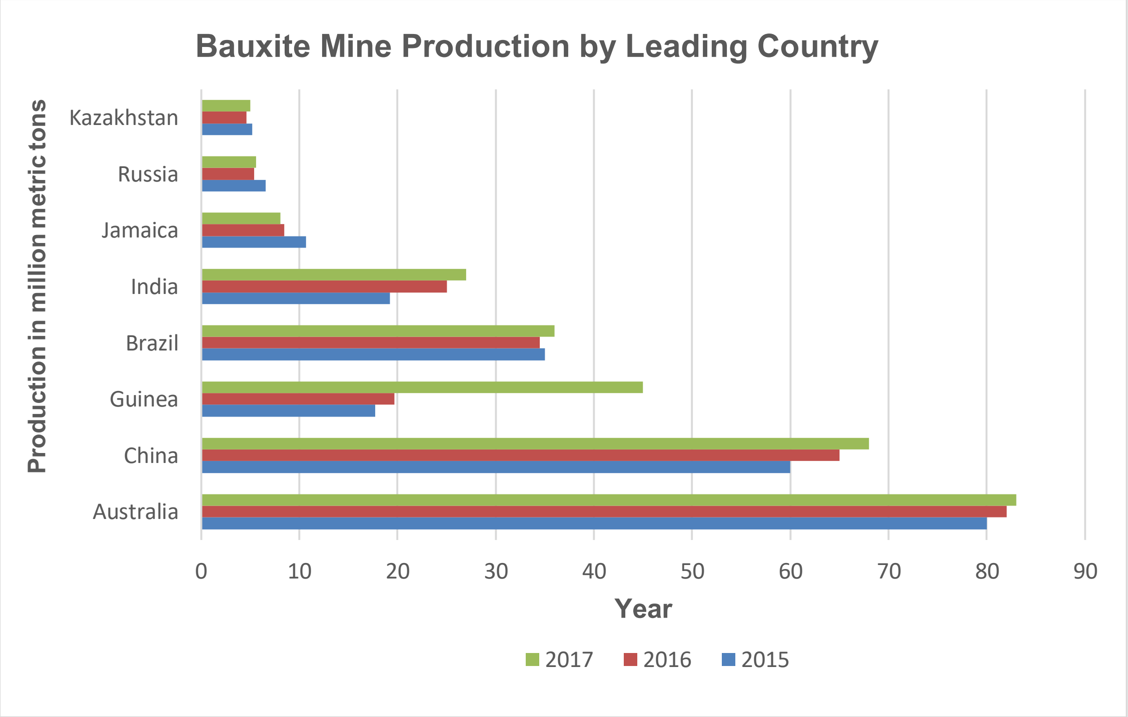

Figure 30. Mine production of bauxite by leading country from 2015 – 2017, in million metric tons (USGS, 2017).

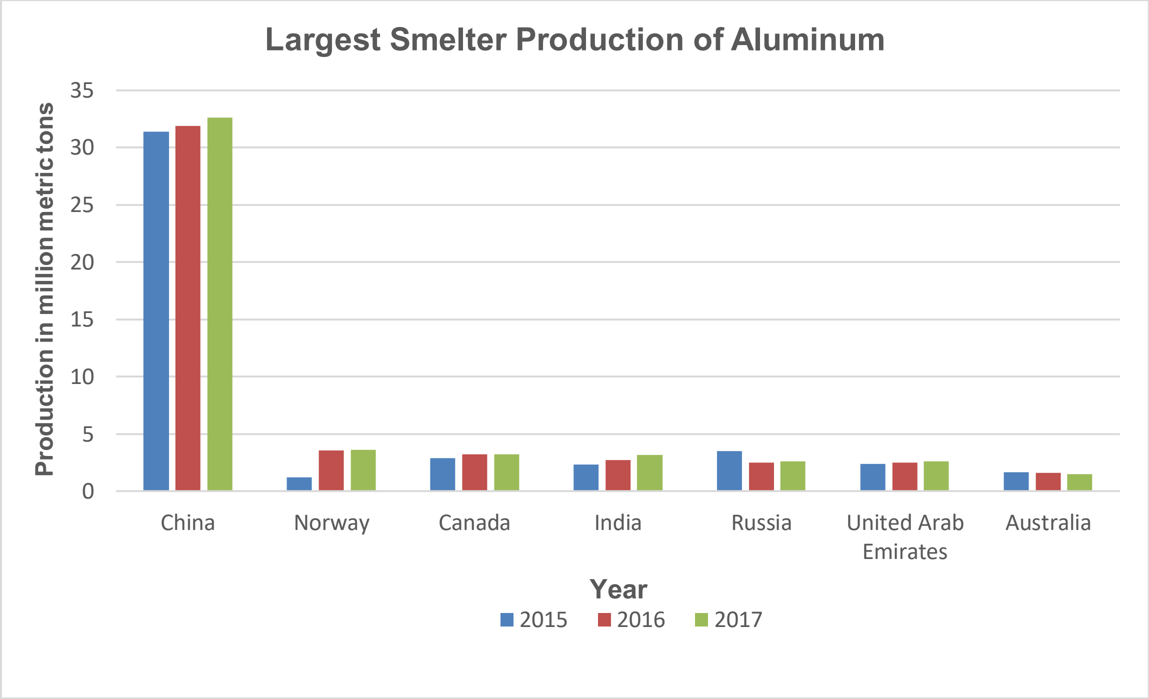

Figure 31. Largest smelter production of aluminum from 2015 – 2017, in million metric tons (USGS, 2017).

Researchers agree that it is very difficult to calculate the volume and nature of the bauxite wastes. There is very little useful information or data about it (Power et al., 2011; Klauber et al., 2011). Subsequently, an estimation of the annual production of bauxite mine wastes worldwide and by leading country has to be calculated based on several assumptions. For example, according to Liu (2014), the production of 1 tonne of alumina generates between 1 and 1.5 tonnes of red mud. Furthermore, according to Lottermoser (2010), for every tonne of bauxite produced, there would be at least the same amount of solid waste generated, and between 20 - 25 percent of this solid waste is considered mine tailings.

Taken the previous hypothesis proposed by Lottermoser (2010), it is possible to state that in 2017, the production of bauxite solid mine waste reached at least 280 million metric tons, almost 20 more million that in 2016 (See Figure 32). Additionally, the production of bauxite mine tailings for the same year was around 70 million metric tons (See Figure 33). As it is evident to suppose, the major producers of bauxite mining tailings are Australia, China and Brazil, which 21, 17 and 9 million metric tons of tailings produced, respectively, in 2017 (See Figure 34).

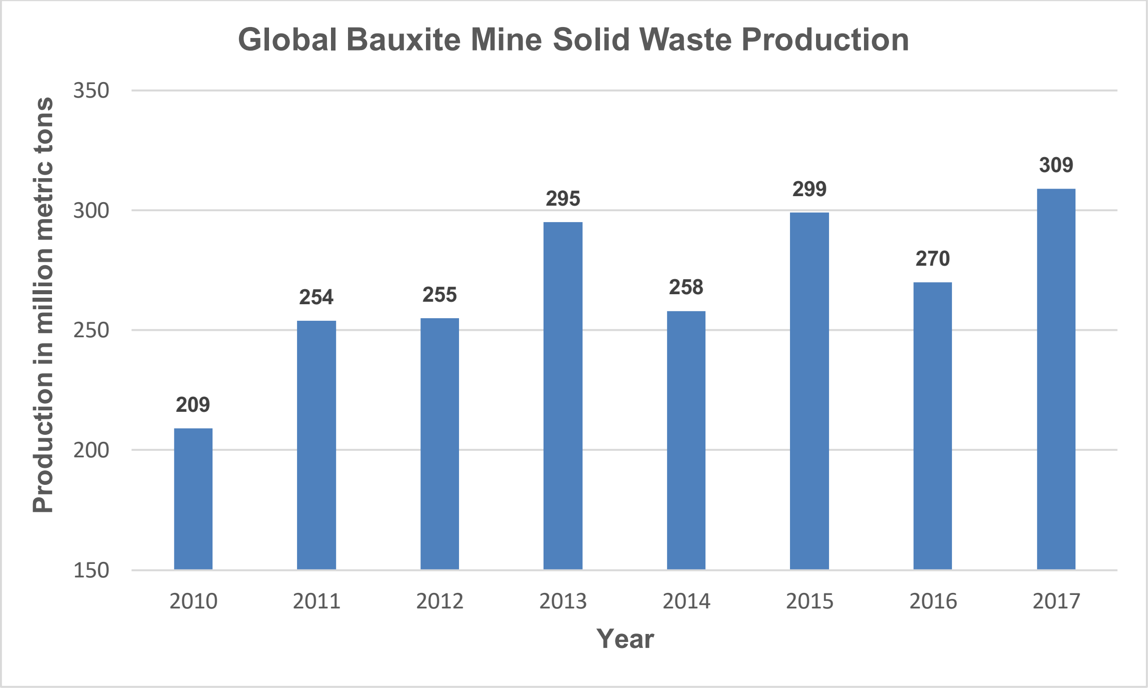

Figure 32. Global production of bauxite mining waste from 2010 - 2017, in million metric tons.

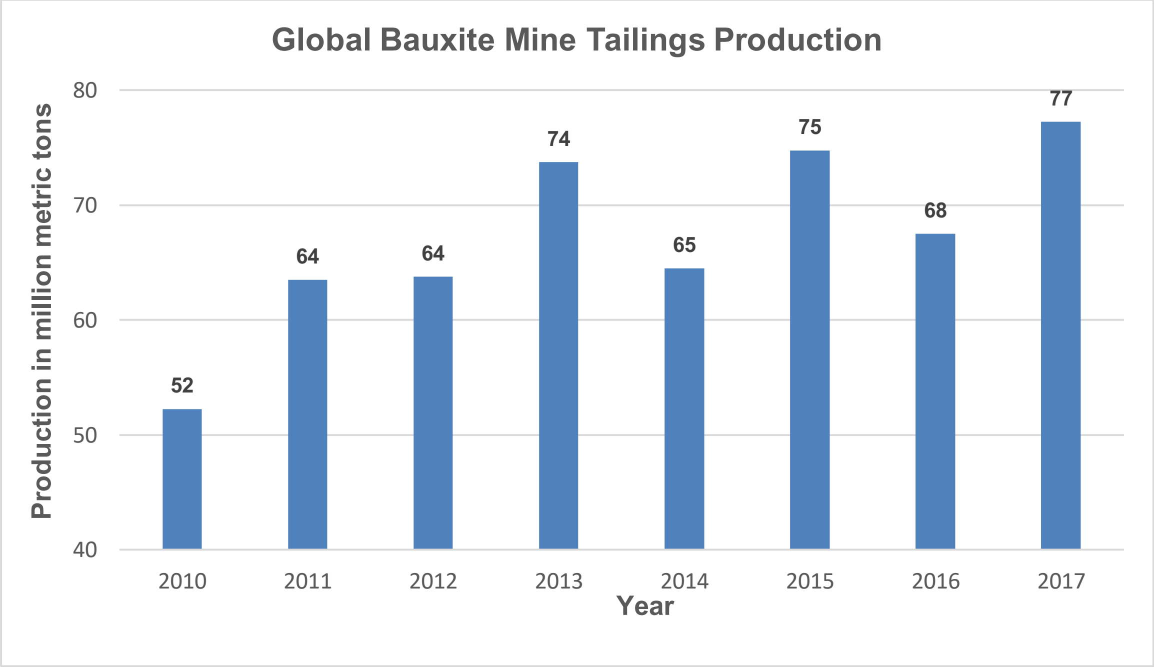

Figure 33. Global production of Bauxite mining tailings from 2010 – 2017, in million metric tons.

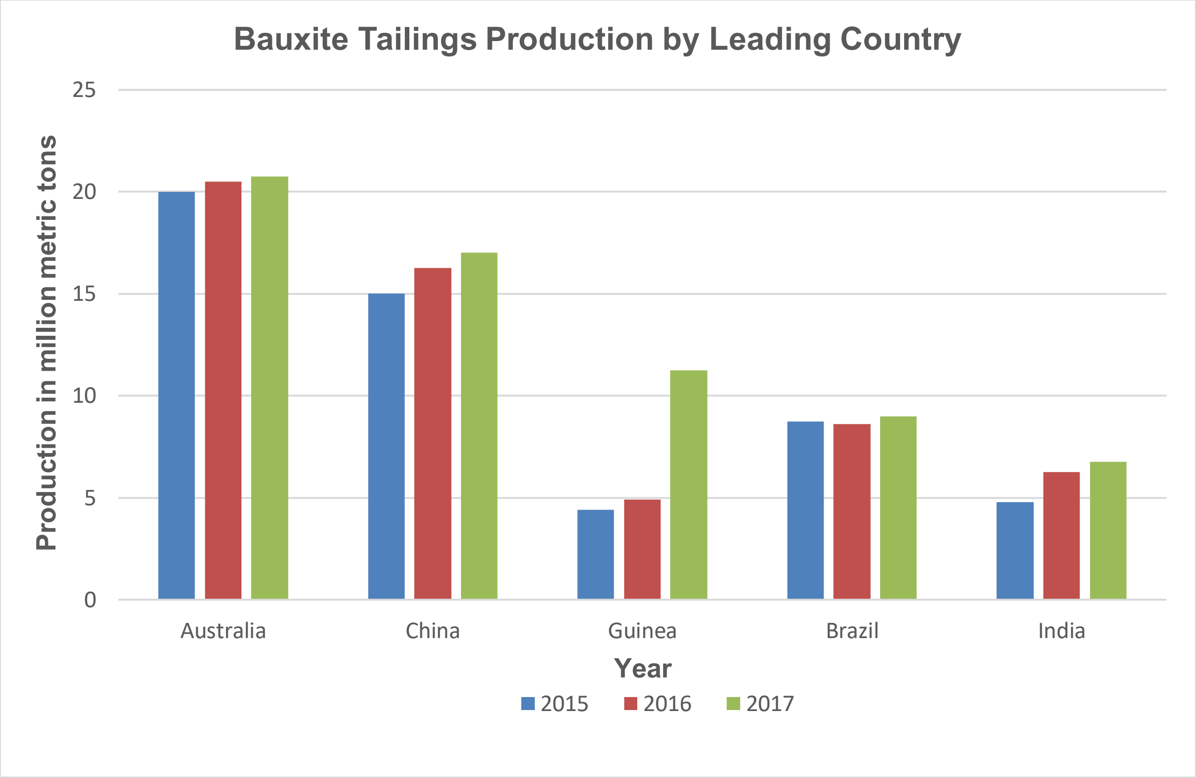

Figure 34. Production of Bauxite mining tailings by leading country from 2015 – 2017, in million metric tons.

4.1.5. Coal Mining Waste Production

According to the International Energy Agency (IEA) (2018), coal is the most important non-renewable natural resource for energy and heat production with a participation of 45% in the global market. In fact, global coal production, including steam coal, coking coal, hard coal and lignite reached more than 7,300 million metric tons in 2017. However, production of coal decreased in more than 500 million metric tons from 2013 (See Figure 35). China, India, United States, Australia, and Indonesia are the major five producers of coal in the world. In 2016, China produced more than 3,000 million metric tons of hard coal. China was and remains by far the leading hard coal producer worldwide (Figure 36) (BMNT, 2018; IEA, 2018).

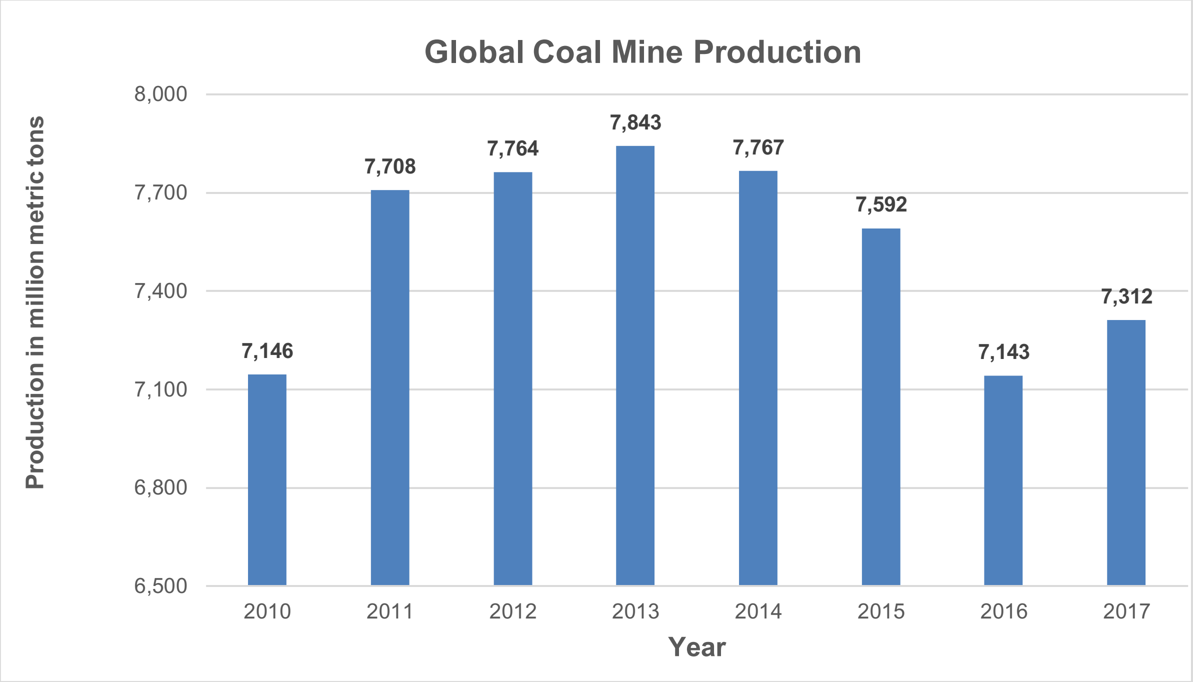

Figure 35. Global production of total coal form 2010 – 2017, in million metric tons (BMNT, 2018)(USGS, 2017).

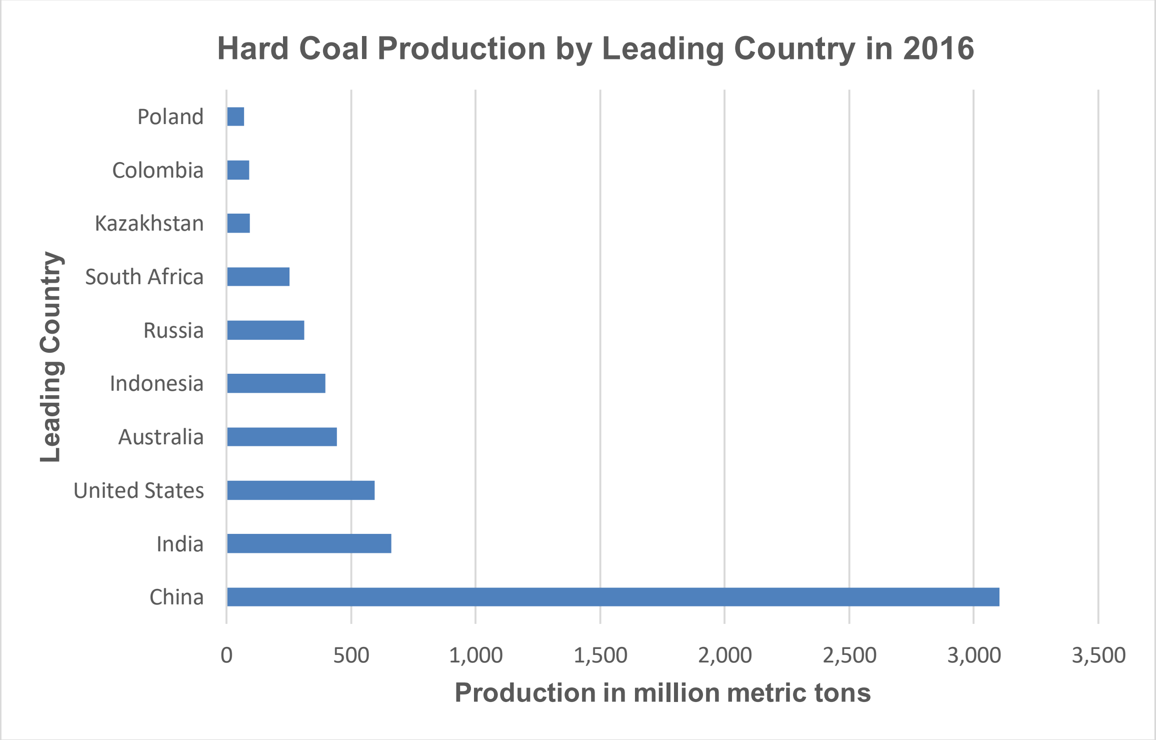

Figure 36. Production of hard coal by leading country in 2016, in million metric tons (USGS, 2017).

The International Energy Outlook report published by the U.S. Energy Information Administration in 2016, predicts an increase in coal consumption between 2012 and 2040, at an average rate of 0.6% per annum (IEA, 2018). However, there is a major problem associated with this increase in the global coal market; mine coal tailings represent a high risk for potential environmental hazards, apart from the generation of greenhouse gasses, processing of coal can also produce acid mine drainage, tailings dam failures, air and water pollution by tailings dam erosion, among others. In coal mining, tailings are generated from fine coal, which signifies about 10 – 20% of the Coal Handling and Preparation Plant (CHPP) (Tang et al., 2012; Adiansyah et al., 2017; Adiansyah and Haque, 2017).

According to Lottermoser (2010), For each tonne of coal consumed, there would have been at least the same amount of solid waste generated, and between 20 – 25% of this solid waste is considered tailings. Consequently, this assumption indicates that in 2017, more than 7,300 million metric tons of solid waste were produced by the coal industry (See Figure 37) and at least 1,8 billion metric tons were tailings (See Figure 38). As it is evident to presume, the major producer of hard coal mining tailings in 2016, were China, India and United States, which more than 770, 160 and 150 million metric tons of tailings produced, respectively (See Figure 39).

Figure 37. Global mining waste production of total coal fom 2010 – 2017, in million metric tons.

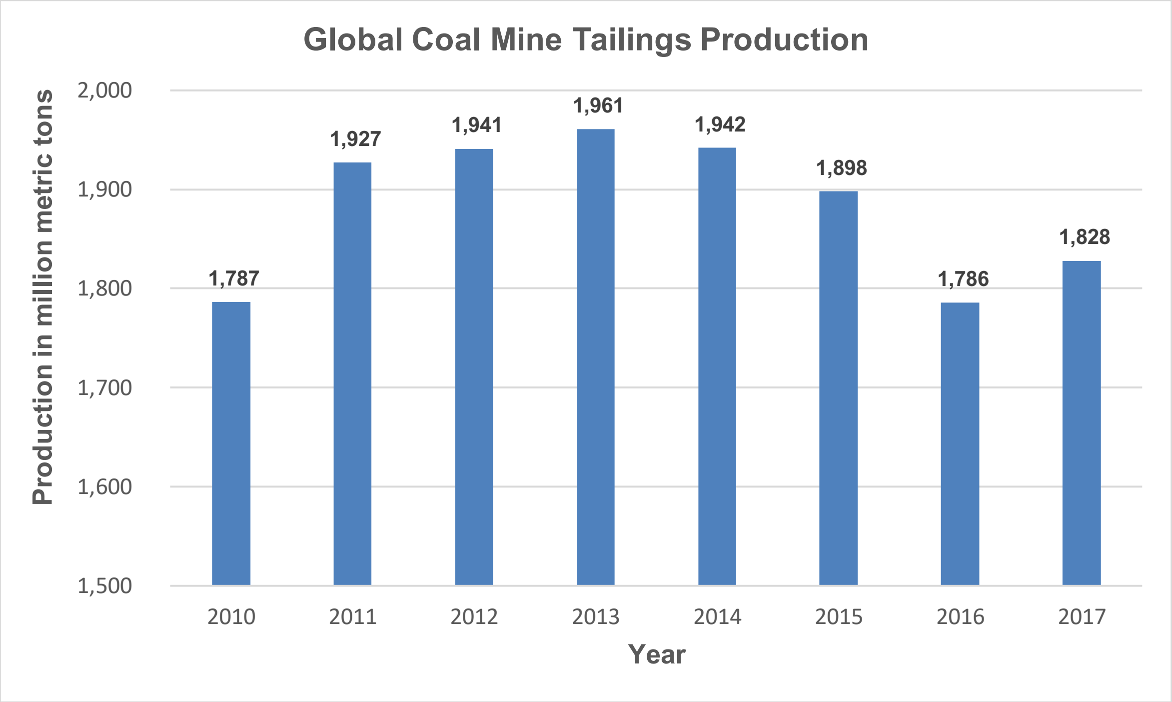

Figure 38. Global production of coal mine tailings from 2010 – 2017, in million metric tons.

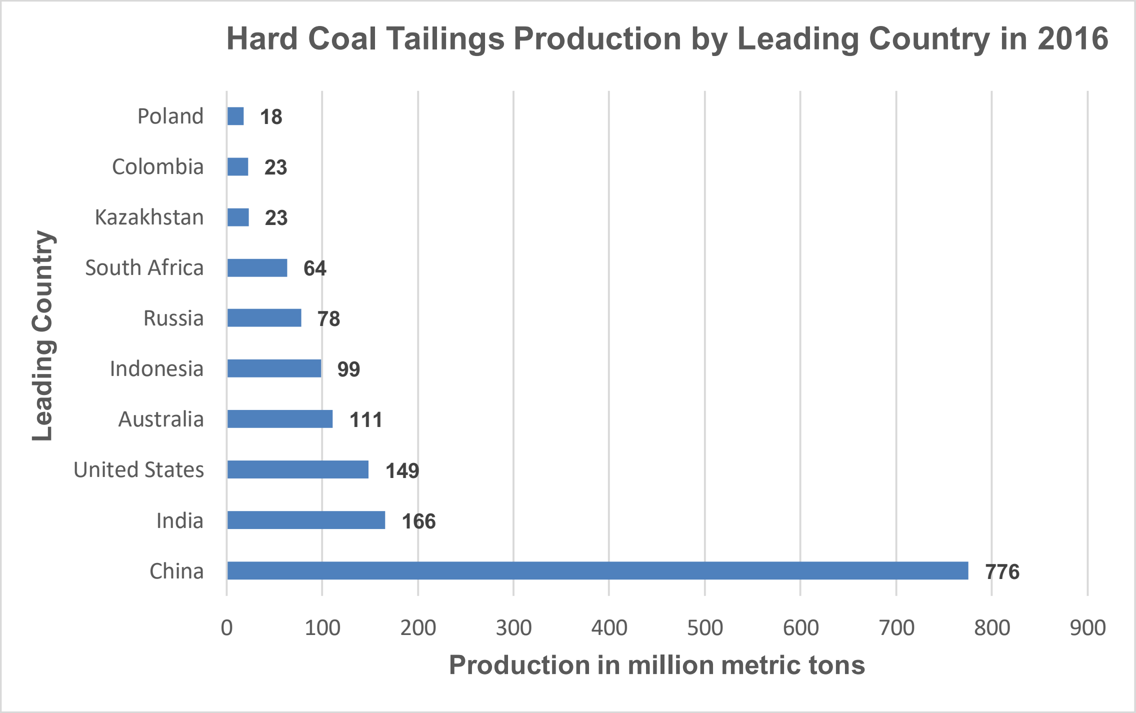

Figure 39. Production of hard coal tailings by leading country in 2016, in million metric tons.

Figure 40 and 41 demonstrate that the generation of solid mine waste by extraction and processing of coal is much higher than for any other mineral or metal as well as the production of mine tailings. This mainly due to the high demand of coal worldwide from different markets. However, gold recovery and processing is the greatest producer of solid mine waste and tailings by a tonne of ore extracted.

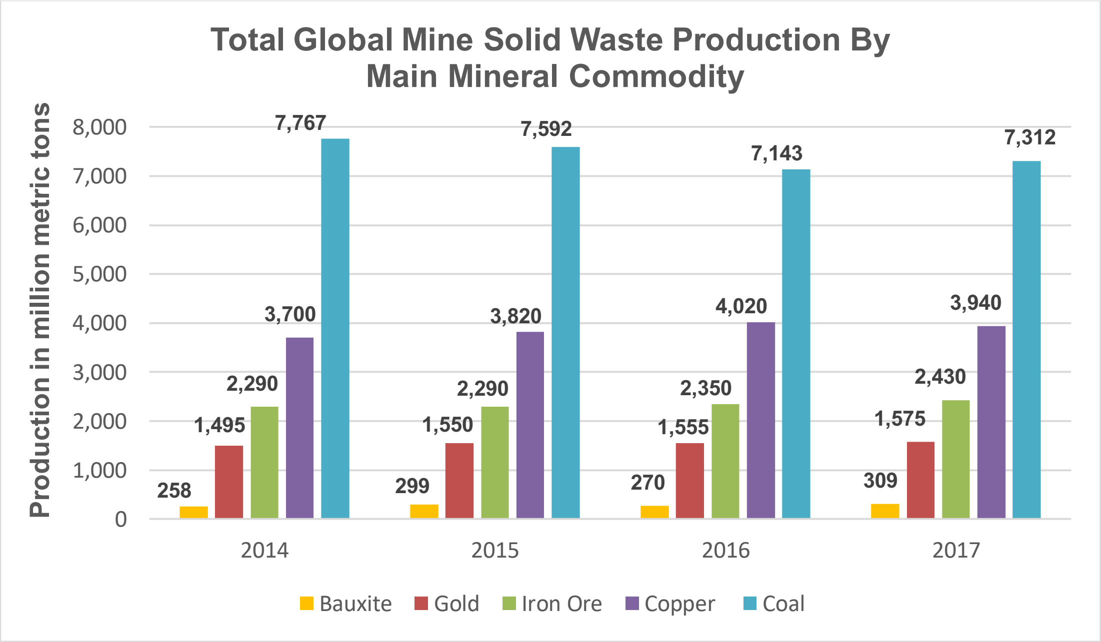

Figure 40. Total global mine solid waste production by main mineral commodity from 2015 – 2017, in million metric tons.

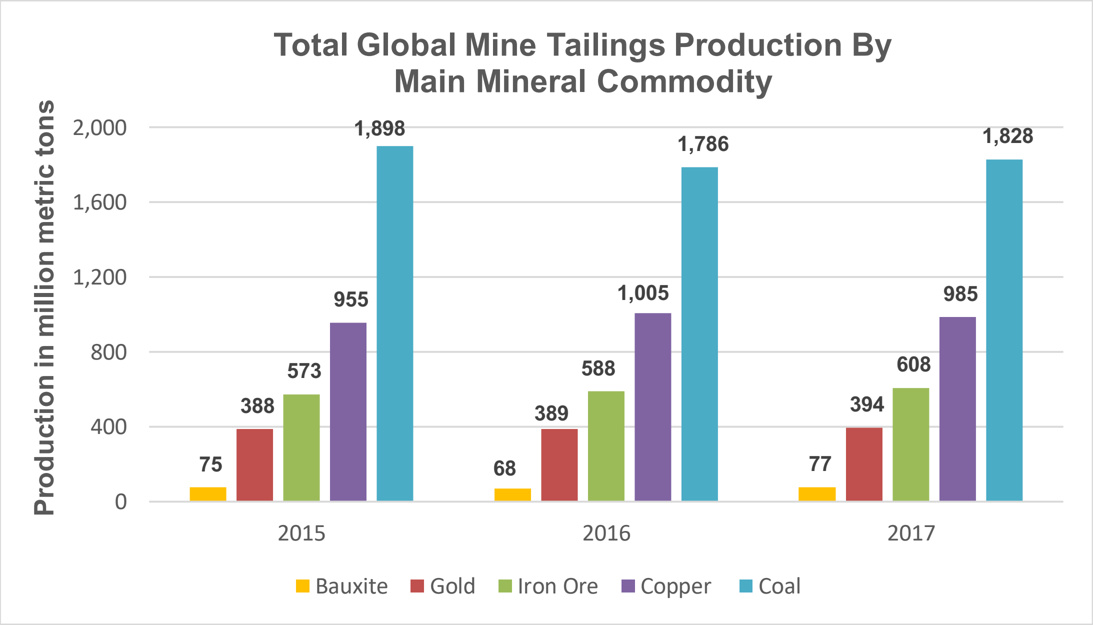

Figure 41. Total global mine tailings production by main mineral commodity from 2015 – 2017, in million metric tons.

5. REUSE, RECYCLING AND REPROCESSING OF MINE TAILINGS DAMS

According to Lottermoser (2011), reprocessing of mine waste is defined as a process designed to use the waste as a "raw material" for producing a valuable product, in the case of mining to recuperate minerals and metals that could not be recuperated in the past. However, reuse of mine waste is described as the practice that involves new applications of the mine waste in its original form for a particular purpose directly without any reprocessing. Recycling on the other hand implicates reprocessing processes in order to recuperate new valuable minerals or metals into the tailings with the aim of converting the mine waste into a new valuable product or application.

The great majority of solid waste produced at mine sites is still placed into tailings storage facilities, and is increasing every year. The effects of poorly and inappropriate mine waste management are well known and described. Many communities and ecosystems have suffered the severe effects of this problematic (Lottermoser, 2010; Kossoff et al., 2014; Hudson-edwards et al., 2011; Schoenberger, 2016a; Carmo et al., 2017).

There is growing concern whether the practices applied by mining companies and government's rehabilitation efforts will be successful in order to protect the environment and the society in the long term from the consequences of inefficient management of mine tailings dams. Reuse, recycling and reprocessing of mine tailings dams are progressively receiving more attention mainly for their contribution to improve the sustainability of the mining business, but also for the benefits that this option offers to all stakeholders directly or indirectly involved in the mining business. Several factors, such improved of metal prices, technology as well as legislation could be one of the situations that in nowadays drive the interest in mine wastes applications and research by mining industry and academics (Cata, 2013; Matinde et al., 2018; Nleya et al., 2016; Ndlovu et al., 2017; Lottermoser, 2011).

The aim of this chapter is to present several examples of existing solutions and to identify the technology applied in each case, which enable improved total resource efficiency and metal extraction, specifically for those minerals highlighted in the previous chapter, which have the highest demand and also are the major producer of mining waste worldwide.

5.1. Tailings Reprocessing

Reprocessing of tailings dams can be a favorable option for both: communities which receive all the environmental and economic benefits, and mining companies which make profit and improve the perception of the mining industry (Kojo et al., 2013; Bellenfant et al., 2013; Ndlovu et al., 2017; Lottermoser, 2011).

The key drivers for the extraction and reprocessing of tailings dams can be highlighted as follows: first of all, extraction and processing of tailings dams are considered to be cheaper than conventional mining extraction because they required fewer resources which supposed less capital of investment and also in many cases some of the existing facilities for the treatment of raw ores can be used for the processing of tailings. Secondly, improve and advance in processing methods has made more economically and efficiently the recuperation of valuables minerals and metals placed in tailings storage facilities which were previously considered as uneconomic. Third, reprocessing of mine tailings is considered a less polluted method that not increase the footprint and not need additional land permits in comparison with traditional mining methods. Finally, the reprocessing of tailings can also have a strong influence in the accessibility of metals and consequently stabilize their prices in the world market (Ndlovu et al., 2017).

5.1.1. Mineral Valle Central (El Teniente Tailings)

Mineral Valle Central (MVC) is a processing plant owned by Amerigo Resources LTD which produces copper and molybdenum concentrates by reprocessing tailings generated by the El Teniente mine, which is owned and operated by Codelco. The MVC operation is located in central Chile, 8 km east of the city of Rancagua and 90 km south of Chile’s capital, Santiago. The MVC operation is placed near two historic tailings dams; Cauquenes and Colihues. The Cauquenes tailings were deposited by El Teniente over the period 1936 to 1977, and the Colihues tailings were deposited over the period 1977 to 1986. Extraction of material from the Colihues deposit ceased in 2015, because there is insufficient capacity to simultaneously process both Fresh Tailings and tailings dams at their maximum rates. However, Colihues tailings reprocessing operations are planned to restart in 2031, when the Cauquenes deposit is depleted (Figure 42) (MVC, 2013; Kojo et al., 2013).

Figure 42. Mineral Valle Central site (MVC, 2013)

The Fresh Tailings that come from El Teniente Mine are transported via gravity to MVC processing plant (36 km long) using a concrete open launder channel (See Figure 43). MVC currently receives approximately 130,000 tonnes per day of Fresh Tailings from El Teniente Colon concentrator. A total of 796 million tonnes of Fresh Tailings at a grade of 0.111% copper and 0.005% Molybdenum is planned to be delivered to MVC's processing facilities by the year 2037, which is the end of the MVC's contract with El Teniente. The Surplus Fresh Tailings material is planned to bypass the MVC's mill and be deposited into the voids created in the Colihues and Cauquenes impoundments (MVC, 2013).

Tailings in the Colihues deposit were extracted via a hydraulic monitoring system using high pressure water guns operating at 30 bar. The monitors work horizontally and vertically, operated by remote control using a hydraulic system of electronic valves that allow them to rotate and advance. A single monitoring unit is capable of sustaining a production rate between 8,000 to 10,000 tonnes per day. (See Figure 44). This method allowed to extract around 35,000 tonnes per day of tailings from Colihues dam. It is required to have mining bench heights 10 m high and access ramps in order to relocate the hydraulic monitors. The depth of the Colihues tailings dam deposit is approximately 50 m, requiring four mining benches (MVC, 2013).

Tailings are extracted from the Cauquenes deposit using a hydraulic monitoring system similar to Colihues. The processing rate of Cauquenes tailings dam is 62,500 tonnes per day and its extraction is anticipated to be complete at the end of 2030. The general method of mineral recuperation applied on Cauquenes tailings can be summarized in four main steps: first, the construction of a sump in the tailings deposit and installation of a vertical slurry pump. Secondly, to start extraction down to 10 m using hydraulic monitors and allow the slurry to drain to slump. Third, transport tailings to the MVC processing plant at a density of 43% solids, and finally, relocation of the monitors sequentially away from the sump to advance the extraction (See Figure 45). This procedure is repeated until the bottom of the tailings deposit is reached, approximately 50 m deep (MVC, 2013).

Furthermore, safety zones are maintained near the walls to ensure the integrity of the walls and decrease the risks of dam failures. For this reason, not all of the tailings are planned to be extracted and approximately 22 million tonnes of tailings are expected to remain in-situ. A total of 30 million tonnes at a grade of 0.27% Cu currently have been repossessed by MVC's. And a total of 305 million tonnes at a grade of 0.267% Cu and 0.021% Mo is planned to be delivered to the MVC's processing facility from Cauquenes in situ resources (MVC, 2013).

Figure 43. El Teniente fresh tailings launder (MVC, 2013).

Figure 44. Colihues hydraulic mining extraction of tailings (MVC, 2013).

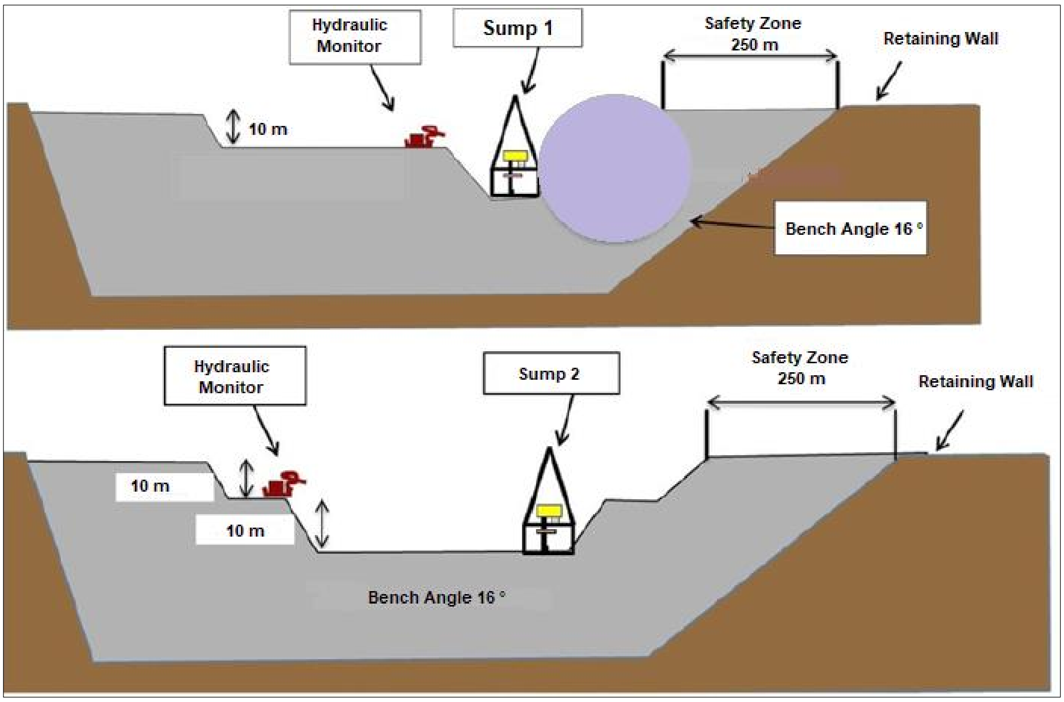

Figure 45. Schematic extraction of Cauquenes Tailings Dam (MVC, 2013).

The existing process plant at MVC recovers copper and molybdenum from Fresh Tailings that come from El Teniente Mine and from tailings extracted from the Cauquenes tailings dam. The MVC processing plant has a capacity of 185,000 tonnes per day and mainly consists of grinding and flotation plants to recover copper and molybdenum concentrates. The tailings slurry is processed in ball mills and flotation cells to produce a bulk copper concentrate. The copper concentrate is treated in the molybdenum separation facility to produce a molybdenum concentrate. The final copper and molybdenum concentrates are filtered, dried and bagged for shipment to smelters. Figure 46 shows the method applied to MVC processing tailings plant (MVC 2013; Kojo et al., 2013).

Once the tailings have been repossessed by MVC, they are returned to the El Teniente tailings washing plant and transported to the Carén tailings dam located approximately 50 km to the west of the MVC site. In 2016, MVC processed 63 million tonnes of tailings and produced 57 million pounds of copper and 0.5 million pounds of molybdenum. According to Kojo (2013), the capital cost of the production and the operation costs were considered very low due to two main reasons; first of all, there was no investment required for the construction of the mine itself and secondly, the material (tailings) was already mined (MVC, 2013; Kojo et al., 2013).

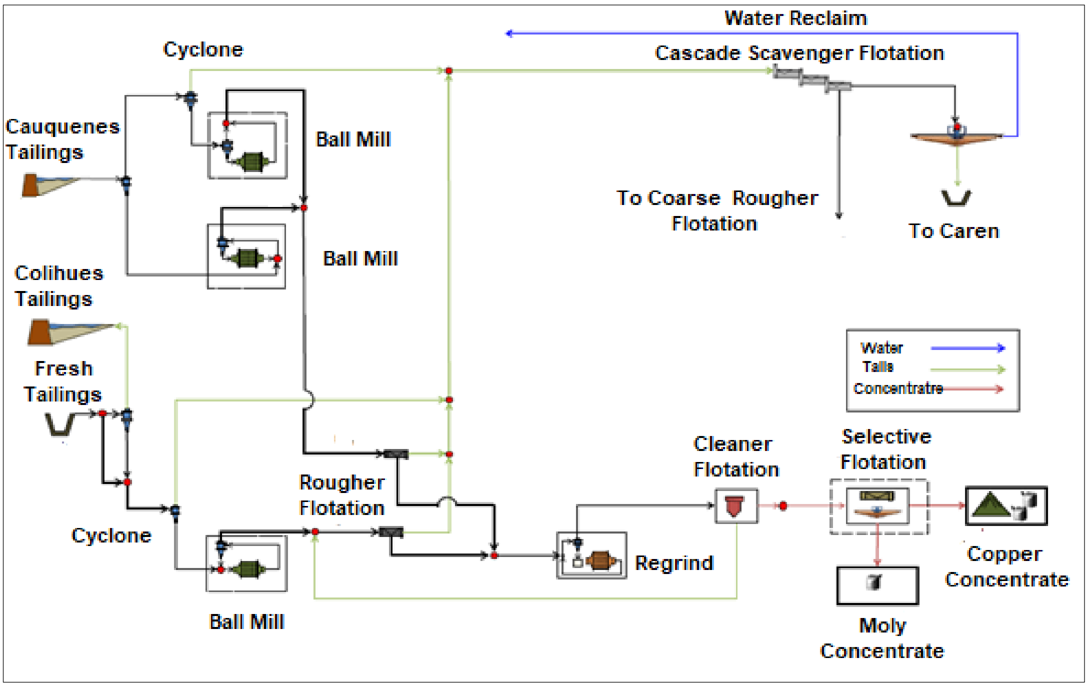

Figure 46. Simplify MVC flow sheet (MVC, 2013).

5.1.2. DRDGOLD

DRDGOLD is the only South African gold mining company focused exclusively on the reprocessing of surface gold tailings, and it is considered a world leader in the recovery of gold from dam tailings. In 2018, DRDGOLD produced more than 150,000 ounces of gold, generated 170 million dollars in revenue and more than 100 million dollars on capital projects (property, plant and equipment). Additionally, in the same year the company rehabilitated approximately 200 ha of land (DRDGOLD, 2018).

DRDGOLD operates four metallurgical plants; Knights plant in Germiston, Crown Mines and City Deep (both former plants), and the company's flagship metallurgical plant, Ergo, located about 50 km east of Johannesburg in Brakpan. Knights and Ergo plants together comprise what is probably the world's largest gold surface tailings retreatment facility. The new consolidated Ergo operation processes about 2.0 Mt to 2.1 Mt of gold-bearing material per month. In 2016, the company declared Mineral Resources of 50.67 Million and Mineral Reserves of 1.84 Million ounces, respectively (DRDGOLD, 2018).

The Ergo Tailings Mine is composed of sand and slimes dumps which are the result of the less efficient 'stamp-milling' process used in the early gold mining years. Sand dumps are recovered mechanically using front end loader machine which is a type of tractor, that has a front-mounted square wide bucket to scoop up loose material from the ground and move it from one place to another, this machine places sand onto conveyor belts. Then, the sand is fed onto a screen where water is added to wash the sand into a sump, from where it is pumped to the reprocessing tailings plant. While, slime dams are taken down using a hydraulic monitoring system (Hydraulic Cannon) that spray jets of high pressure water at the target area (See Figure 47). The resulting slurry is then pumped via pipeline to the retreatment plant for further processing. In fact, the company built 50 km pipeline in order to bring to account the resources on the western side of town from Crown project to Ergo's processing plant. The pipeline was constructed of steel and innovative technology was used to install the high-density polyurethane (HDPE) lining (See figure 48) (DRDGOLD, 2018).

Figure 47. DRDGOLD hydraulic mining extraction of tailings (Madiba, 2019).

Figure 48. DRDGOLD transportation of tailings by pipeline system (DRDGOLD, 2018).

The Ergo recovery gold method consists in flotation/Fine grinds and Carbon-In Leach process known as CIL. The slurry material from the tailings dams is transported to the processing plant through the pipeline system. Then, the process of gold recovery starts with the first step which consists in the flotation of the slurry material using banks of flotation cells. Later, the material is conditioned using collectors and frothers in order to separate the material into two streams. One stream, the flotation concentrate, contains the sulphides which are enriched with gold while the second stream, the flotation tails, is made up of lower-grade siliceous material. This stream is treated by the conventional CIL process, which is the treatment process that has been used for the past 30 years with an extraction efficiency of 39% to 40% (DRDGOLD, 2018).

The flotation concentrate stream is subjected to the new fine-grind process which involves milling the slurry material with tiny beads. At this stage the milled product, has been liberated from the sulphides, making recovery of the previously encapsulated gold easier as it comes into contact with cyanide during the process that follows. The extraction efficiency of this process is about 75 percent. Finally, activated carbon is applied in order to capture the dissolved gold, and the 'loaded carbon' in each circuit enters the carbon treatment section where the gold is removed from the carbon. The carbon then returns to the CIL circuit via a regeneration kiln. Once the gold has been separated, it undergoes a process called electro-winning where the gold is precipitated, calcined and smelted in the existing "smelthouse" at DRDGOLD installations (DRDGOLD, 2018).

5.1.3. Barberton Tailings Retreatment Plant (BTRP)

Barberton Tailings Retreatment Plant (BTRP) is a reprocessing gold tailings project which belongs to Pan African Resources (PAR). This company is a mid-tier African-focused precious metals producer, with a production capacity in excess of 190,000 ounces (Oz) of gold per annum. PAR gold mining operations produce gold from underground operations and from surface tailings. The group is one of the lowest cash-cost producers of gold in Southern Africa. PAR operates three major projects in Africa; Evander Mines, Phoenix Platinum and Barberton Mines, which are the company's flagship gold project. The BTRP is located in Barberton Mines, which is situated in Mpumalanga, a province in eastern South Africa (PAR, 2018).

BTRP is the result of successful metallurgical test work carried out on the Bramber tailings dam, which is the dam of Barberton underground gold mine. Its construction commenced in April 2012, and was completed on schedule and within budget, and achieved its inaugural gold production in June 2013. BTRP project was designed to reprocessed 100,000 tonnes of gold tailings per month at an estimated average cash cost of US$800/Oz. In fact, gold was produced by the Barberton Tailings Retreatment Plant at the exceptionally low all-in cost of $332/Oz in 2016. BTRP has a capacity of 30,000 Oz of gold per annum, increasing the production at Barberton Mines' to 100,000 Oz per year. Barberton Tailings Retreatment Plant contributes to 19% of Barberton Mines' gold production. In 2018, BTRP produced 17,504 ounces of gold. This project will be operated for at least 15 years (PAR, 2018).

The information found suggests that Barberton Tailings Retreatment Project uses a non-selective mining method for the recuperation of mine tailings dam whereby the whole of the mineral deposit is mined in a predetermined sequence. Hydraulic mining (hydraulic cannon) and pipeline system have been selected as the mining method as it is a proven technology, cost effective and technically and operationally well understood. The mining method allows for 100% extraction of the targeted mineral deposit (See Figure 49).

The BTRP plant is expected to treat about 12,000 tonnes per month of current tailings via a pipeline from the existing Fairview Mine concentrator and BIOX® plant, and some 88,000 tonnes per month from the oldest tailings dumps. This reprocessing plant operates a carbon in leach process followed by electrowinning and smelting to produce a saleable gold product. Barberton Tailings Retreatment Plant resources are more than 21 Mt and approximately more than 13 Mt of reserves, with a head grade of 1.60 grams per tonne (PAR, 2018; Creamer, 2016).

Figure 49. BTRP hydraulic mining method (PAR, 2018).

5.1.4. New Century Mine

Century Mine is located at Lawn Hill, 250 km north-west of Mount Isa in the Lower Gulf of Carpentaria, in northern Australia. It began open-pit production in 1999, during 16 years of operation, Century was one of the largest zinc mines in the world until was closed in 2016, due to low prices and depleted reserves. However, the company New Century Resources start the retreatment of tailings at Century Mine in 2018 (NCR, 2019).

New Century has an estimated production capacity, based on current ore reserves only, of 264,000 tonnes and 3 Million ounces of zinc and silver per year, respectively. The initial mine life is more than 6 years. However, In-situ Mineral Resources also provide potential for mine life extension and the Company is currently engaged in active exploration programs. The extraction of tailings is done through hydraulic mining or hydraulic cannons, high pressure water pumped from the adjacent evaporation dam is used to convert the tailings into a slurry, which is channeled and pumped throughout steel pipeline to the New Century Processing Plant for reprocessing, prior to being pumped to the existing open pit for final deposition (See Figure 50). The processing plant was refurbished in order to re-process the tailings. The company has a processing plant with a current capacity of 8 Million tonnes of tailings per annum with the aim of increase capacity to almost 13 million metric tons annually (See Figure 51) (NCR, 2019).

Figure 50. Hydraulic exploitation of New Century Tailings Deposit (NCR, 2019).

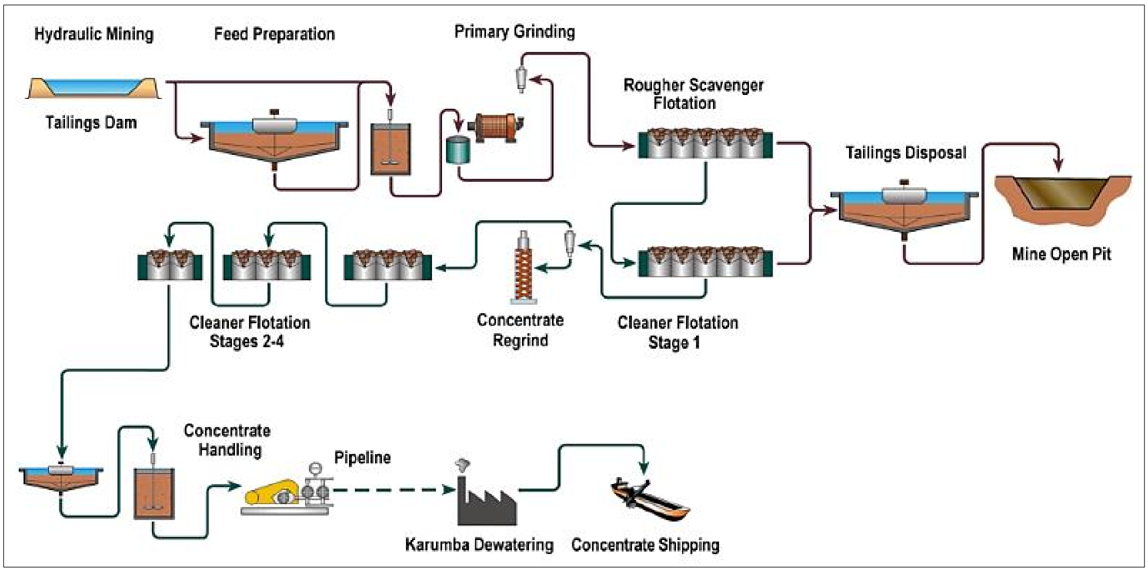

Figure 51. Process overview of tailings at Century Tailings Deposit (NCR, 2019).

5.1.5. Sylvania Dump Operations (SDO)

Sylvania Platinum Limited (Sylvania) is a rapidly expanding producer of the platinum group metals (PGMs) platinum, palladium and rhodium, with two distinct lines of business: the retreatment of PGM-rich chrome tailings material from the mines and the development of shallow mining operations and processing methods for low-cost PGM extraction. The Sylvania Dump Operations currently include five fully operational chrome tailings processing complexes located in South Africa; Millsell, and Mooinooi ROM on the western limb of the Bushveld Igneous Complex (BIC), and Lannex, Doornbosch and Tweefontein on the eastern limb (SPL, 2018).

Millsell and Mooinooi ROM Dam Operations are located in the North West Province, in the town of Rustenburg, South Africa. Millsell has a production capacity of 25,000 tonnes per month of combined dump material and current arisings, while Mooinooi ROM processing tailings plant has a capacity of 60,000 tonnes per month. The other projects; Lannex, Doornbosch and Tweefontein are located in Mpumalanga Province, in the town of Steelpoort, South Africa. With a production capacity of 45,000, 25,000 and 42,000 tonnes per month of combined tailings materials and current arisings, respectively. SDO is the largest PGM producer from chrome tailings retreatment in the industry. It has a current annual production capacity of 75,000 ounces – 78,000 ounces, with a Low cost operation between $450 - $550 per ounce (SPL, 2018).

The method applied in Sylvania Dump Operations for tailings retreatment basically includes the recuperation of tailings by high pressure water monitoring or hydraulic cannon, ball milling, rougher flotation, rougher concentrate regrinding and recleaner flotation system. The rougher concentrate is reground in a mill permitting smeltable concentrate grades to be produced from the oxidized, slow floating tailings (See Figure 52) (Buys et al., 2004).

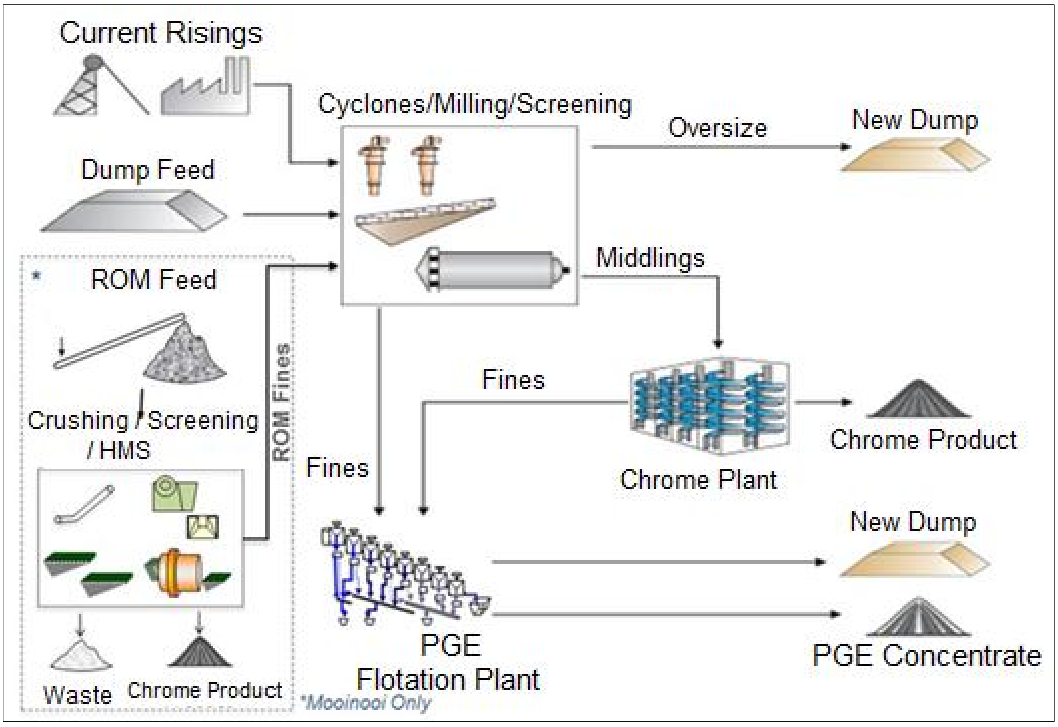

Figure 52. Simplify flowsheet of Sylvania Dum operation process (SPL, 2018).

5.1.6. The Nchanga Tailings Leach Plant (TLP)

The Nchanga Tailings Leach Plant (TLP) is located in Zambia, Africa. It is one of the largest of its kind in the world, it reprocesses tailings from the Nchanga tailings dam to produce copper. TLP belongs to Konkola Copper Mine PLC (KCM), one of Africa's largest integrated copper producers, it is a subsidiary of Vedanta Resources PLC, one of the world’s largest diversified natural resource companies. TLP extracts copper directly to cathodes from concentrate solution using electrolysis. The initial process was based on the acid leach-cementation method. However, in 1974, the plant was converted into Solvent Extraction-Electrowinning System (SX-EW) (KCM, 2019; Ndlovu et al., 2017).

The TLP currently produces about 80,000 tonnes annum of copper via cathode. The tailings that comes from Nchanga tailings dam are dewatered before being leached by the implementation of sulphuric acid and SX refine. Then, the process of Counter-Current Decantation is applied in order to achieve separation of the tailings between liquid and solid. According to Ndlovu (2017), the introduction of SX-EW system in the Nchanga Tailings Leach Plant increased the recuperation of copper from 54,000 tonnes to 100,000 tonnes of copper per year through the retreatment of 10 million metric tonnes of tailings annually (Ndlovu et al., 2017; Sole et al., 2005).

5.2. Tailings Reuse or/and Recycling

As it has been studied and demonstrated for many authors, the best way to mitigate the negative impacts produced by tailings storage facilities is through the application of methodologies which reduce the volume of waste produced during the mining process. Some authors believe that it could be done using an integrated waste management approach that incorporates process recycling and applications for tailings dams in different markets (Lottermoser, 2011; Matinde et al., 2018; Ndlovu et al., 2017; Sibanda and Broadhurst, 2018). In this section several applications for tailings dams were identified, such as using tailings for construction materials, ceramic manufacturing, cement industry, backfilling in open pit and underground mining, stone paper, among others. Each of these uses identified is discussed briefly in the following section.

5.2.1. Tailings Utilization in the Construction Industry

5.2.1.1. Utilization as Aggregate in Concrete

There is a need for an alternative material to be used as aggregate concrete due to the number of quarries for aggregate are gradually decreasing. If mine tailings could be used as a natural aggregate in concrete, it will be a great opportunity to deal with the problematic of mine tailings dams and at the same time providing cheaper and sustainable alternatives in concrete production (Ndlovu et al., 2017).

Li et al (2010), studied the application of iron ore tailings (IOTs) as a replacement material in the production of Portland cement. The researchers used the residue obtained after iron removal from iron ore tailings to produce cement of high quality according to Chinese standards (Li et al., 2010b). Huang et al (2013), found that the utilization of IOTs as aggregate in the production of Engineered Cementitious Composites (ECC) can achieve tensile and compressive properties comparable to ECC with typically-used micro-silica sand. Kuranchie (2015), studied the feasibility of using Australian iron ore tailings as both fine and coarse aggregates in making concrete. The author established that the concrete with tailings aggregates had a lower potential for corrosion and a low vulnerability to acid attack due to high pH values of the resulting combination. Furthermore, the research found that the uniaxial compressive strength of the concrete with iron ore tailings aggregates is higher than concrete with conventional aggregates.

Shettima et al (2016), stated that the concrete workability was reduced with iron ore tailings while all other strength and modulus of elasticity data were consistently higher than conventional concrete at all levels of replacement. The researchers recommended that IOTs should be used in concrete as a sand replacement to minimize environmental problems, cost and natural resource depletion. Shwetha (2017), investigated the utilization of iron ore tailings as fine aggregates and ground granulated blast-furnace slag (GGBS) as partial substitute in concrete. The author concluded that concrete with mining waste as fine aggregate and GGBS content up to 50 - 60% can be used for flooring purposes which results in high decrease in cost. Kumar et al (2015), also used the iron ore tailings as a replacement material for fine aggregates in cement concrete pavements. Their results showed that 40% IOTs could be used as replacement to give an optimum compressive strength.

There are other sources of mine tailings which have been identified as natural aggregates for the construction industry. For example, Onuaguluchi and Eren (2012), studied the use of copper tailings as an additive in cement mortars. They discovered that all the samples containing copper tailings showed superior resistance to abrasion and impact. Thomas et al (2013), investigated the suitability of copper tailing in cement concrete as a partial replacement of natural river sand. The researchers found that copper tailings could be utilized for the partial replacement of up to 60% of natural fine aggregates, copper tailings concrete exhibited good strength and durability characteristics and was further found to be suitable for applications in a number of construction activities.

Widojoko (2013), examined the use of gold mine tailings utilization as fine aggregate material for producing mortar based on concept of green technology. They established that the use of the tailings by 25%, has the best result in compressive strength. In a similar work by Çelik et al (2006), the authors studied the utilization of gold tailings as an additive in Portland cement. The researchers discovered that gold tailings are a viable additive in the production of Portland cement, and this sample with up to 25% gold tailings within the clinker mix produced cement of the required standard in terms of comprehensive strength.

The information presented in this section suggests that the implementation of tailings dams as a raw material for their utilization as a natural aggregate in concrete and as additive in cement production could be a possible environmental solution for proper management of mine tailings. However, according to Ndlovu et al (2017), many minerals processing waste materials have limited potential for use as aggregates due to their variable metal compositions, fine grain size content, the propensity for acid generation, especially for sulphide-containing materials and their high cost production. Nevertheless, these tailings have shown many properties and advantages for the construction industry, which indicates that more research in this field is necessary.

5.2.1.2. Utilization as Brick Making

According to Ndlovu (2019), the popularity in the application of tailings dams for the production of bricks is basically because of the composition of these waste materials is closely similar to that of the common clay material used in the conventional brick making. Some authors have stated that gold tailings are an alternative source for brick making. However, they agree that the use of additives is mandatory in the tailings brick mixture in order to increase the compressive strengths of the bricks. The addition of cement has resulted as the preferred additive (Zhang, 2014; Roy, 2007; Kiventerä et al., 2016).

In South Africa, was studied the possibility of reusing the Witwatersrand gold mine tailings for brickmaking obtaining positive results (Malatse and Ndlovu, 2015). In India, Roy et al (2007), studied the feasibility of using gold mill tailings from Kolar Gold Fields, in Karnataka, India, for brick production. Chen et al (2011), investigated the possibility of making construction bricks by using hematite tailings from Western

Hubei province of China. They mixed the hematite tailings with clay and class F fly ash in different proportions. Kuranchie (2015), explores the potential of using mine tailings available in Western Australia for brick manufacturing.

In United States of America, Ahmari and Zhang (2012), investigated the feasibility of utilizing copper mine tailings from Mission Mine operations of ASARCO LLC in Tucson, Arizona, for the production of eco-friendly bricks based on the geopolymerization technology, which is the reaction of amorphous Al and Si-phases and/or aluminosilicates with a highly concentrated alkali hydroxide-silicate solution to generate a stable material called a “geopolymer” structures with interconnected Si-O-Al-O-Si bonds. In this case the bricks were formed by mixing the copper mine tailings with sodium hydroxide (NaOH) solution. And then, compressing the mixture within a mold under a specified pressure and curing the bricks at slightly elevated temperatures. This method differs from the conventional one because it does not follow the common steps of using clay and shale and firing at high kiln temperatures (Park et al., 2018; Kuranchie, 2015).

According to Zhang (2013), the commercial production of bricks from waste materials is still very limited due to a couple possible reasons; First of all, the methods used for production of brick from mining waste require high capital investment. Secondly, the lack of relevant standards, government policy and public acceptance and education in relation with reuse and recycling of waste.

5.2.2. Tailings Utilization as Tiles and Glass Ceramic Products

Utilization or replacement of raw materials by mine tailings have been one of the major interest for the ceramic industry. Actually, the ceramic industry is considered one of the drivers in the use of industrial tailings. According to researchers, iron ore tailings are fine, stable, and crystalline material which are made principally by iron oxides, silica, alumina and other minor minerals. This composition is similar to that of the clay used in the ceramic industry, for this reason IOTs can be used in the ceramic industry. Moreover, If tailings have a high concentration of silicon and high sodium and potassium content they could be used as raw materials for glass production, this one being a good option for solid mine waste recycling and control of environmental pollution (Fontes et al., 2019; Da Silva et al., 2014).

Da Silva et al (2014), studied the recovery and recycling of tailings from the concentration of iron ore for the production of ceramic. The results of this investigation indicated that the addition of IOTs to the ceramic mass increases its porosity and reduce the water absorption, also increases its flexural strength and decreases its density, properties that are wanted for the production of ceramics. In a related work by Fontes et al (2019), the potential use of iron ore tailings in the manufacture of ceramic tiles was investigated. The authors, found the same advantages that Da Silva and concluded that IOTS can be used in the production of porcelain tiles. However, they stated that the nonappearance of mullite or porcelanitte (a silicate mineral) after firing, is the main disadvantages for the direct application of iron ore tailings in the production of ceramics.

Copper and gold mine tailings have also been tested in the manufacture of tiles and glass ceramic products. In 1999, an investigation about the possibility of the production of unglazed tiles by mixing copper tailings with other raw materials was conducted. They found that copper tailings under specific conditions presents good mechanical properties and acid resistance for their application in the ceramic industry (Marghussian and Maghsoodipoor, 1999). In a similar work by Yang et al (2013), was found that is achievable to prepare the glass–ceramics with light-color and recover the iron from copper slag at the same time, which can greatly improve the comprehensive utilization of copper slag. Liu et al (2015), assessed the used of gold tailings as a resource in place of clay in the production of ceramic products. The researchers found that after further improvements these particular gold mine tailings studied can be made into ceramic tiles, domestic ceramic bodies, and other kinds of ceramic bodies for commercial and industrial purposes.

5.2.3. Tailings Utilization as Extenders in Paints

Solid part of the paint system includes pigments and extenders. The pigment contributes to color, hiding and tinting, while the extender imparts mechanical properties of the coatings. There are mainly used to improve durability, resistance to corrosion and decreasing of costs (Ossi and Dilim, 2015). Saxena and Dhimole (2006), studied the characterization of copper tailing waste and its potential application as an extender in paints. This investigation found that some properties such hardness, adhesion and resistance to impact and abrasion have better performance than in a conventional extender, which indicates that copper tailing waste has good potential to be used as an extender in paints with respect to specific gravity, oil absorption and pH.

Barros et al (2018), investigated the use of iron ore tailings from tailings dams as pigment in the production of a paint for buildings. The author found that the pigments based on iron ore tailings present satisfactory results regarding durability with lower costs than traditional pigments. In addition, they concluded that the IOT is technically feasible to produce pigments for building paints prepared in situ.

5.2.4. Tailings Utilization as Stone Paper

Stone paper is advertised as eco-friendly technique, as it does not use trees, water, chlorine, acids or petroleum in its manufacture. It is primarily made from calcium carbonate. An economic feasibility study led by the Zero Emissions Research and Initiatives (ZERI) which is a global network of creative minds, seeking solutions to the ever increasing problems of the world indicated that the use of tailings is more cost effective than crushed rock; paper production is approximately 40% less than those for conventional pulp-based paper production (Sibanda and Broadhurst, 2018).

In South Africa, the possibility to establish a stone paper factory which utilizes the contents of tailing dams at mine dumps to produce stone paper have been studied. In Johannesburg, there are many tailing dams across the city and the project has the potential to attract investment from mining companies who see this application for reuse and recycling of mining tailings dams as a great opportunity to deal with the environmental pollution and risks related with solid mine wastes (Knopjes, 2015).

The literature review and information presented in this chapter indicates that there are many opportunities for the reuse and recycling of mine tailings, specially utilization of tailings in metal producing, manufacturing and building industry. However, there are many other potential applications that have been identified (See Table 6). Nevertheless, these new techniques for reuse and recycling of tailings have remained ideas or laboratory trials without wider application. These ideas have not been taken up by industry because they are driven by their practical applications and financial returns.

Waste Type		Reuse and Recycling Option
Mining wastes	**Waste rocks**	• Resource of minerals and metals • Backfill for open voids • Landscaping material • Capping material for waste repositories • Substrate for revegetation at mine sites • Aggregate in embankment, road, pavement, foundation and building construction • Asphalt component • Feedstock for cement and concrete • Sulfidic waste rock as a soil additive to neutralize infertile alkaline agricultural soils
	Mine drainage sludges	• Extraction of hydrous ferric oxides for paint pigments • Extraction of Mn for pottery glaze • Flocculant/adsorbent to remove phosphate from sewage and agricultural effluents
Processing wastes	**Tailings**	• Reprocessing to extract minerals and metals • Waste reduction through targeted extraction of valuable minerals, during processing • Sand-rich tailings mixed with cement used as backfill in underground mines • Clay-rich tailings as an amendment to sandy soils and for the manufacturing of bricks, • Cement, floor tiles, sanitary ware and porcelains • Mn-rich tailings used in agro-forestry, building and construction materials, coatings, • Cast resin products, glass, ceramics and glazes • Bauxite tailings as sources of alum • Cu-rich tailings as extenders for paints • Fe-rich tailings mixed with fly ash and sewage sludge as lightweight ceramics • Energy recovery from compost–coal tailings mixtures • Phlogopite-rich tailings for sewage treatment • Phosphate-rich tailings for the extraction of phosphoric acid • Ultramafic tailings for the production of glass and rock wool • Carbon dioxide sequestration in ultramafic tailings and waste rocks
Metallurgical waste	**Bauxite red mud**	• Treatment of agricultural and industrial effluents • Raw material for glass, tiles, cements, ceramics, aggregate and bricks • Treatment of AMD waters • Carbon dioxide sequestration
	Metal smelting slag	• Production of concrete and cement • Use as filling, ballast, abrasive and aggregate • Extraction of metals (e.g. Cu, Pb, Zn, Ag, Au)
	Phosphogypsum	• Soil amendment • Building and construction material • Extraction of elements and compounds (e.g. Calcium sulfate)

Table 6. Common options for reuse and recycling for mining, processing and metallurgical wastes accumulating at mine site (Lottermoser, 2011).

5.2.5. Technology and Potential Projects for Mine Tailings Management

The purpose of this section is to present the current technology applied for mine tailings dam exploitation as well as existing and new potential projects for tailings dams reuse, recycling and reprocessing.

5.2.6. Tailings Exploitation Technology

The most common methods applied to recover mine tailings from tailings dams are hydro mechanization and mechanical dry exploitation. The first one is based on the implementation of hydraulic mining monitors also known as hydraulic cannons (See Figure 53), which were first developed back in the early sixties by a mining company called English China Clays, located in Cornwall, England. Hydraulic mining monitors have been used on tailings dams with two main purposes: for reprocessing or relocation of tailings dams (Engels, 2017).

Hydraulic methods are highly effective when some conditions of the tailings dam, such as geotechnical, geological, physical, mechanical and environmental characteristics are suitable. This technique is considered much simple, efficient and cost effective than mechanical dry methods. The exploitation of a tailings dam is done by high pressure water in order to recover the tailings in sections, washing the material downstream, which is collected in a sump and most of the time transported via steel pipeline to a processing plant. Then, the tailings are stored in a new tailings impoundment that meet the current geotechnical and environmental needs. A typical flow sheet for the extraction of tailings is shown below in figure 54 (Engels et al., 2004).

According to Engels et al (2004), Hydraulic monitors can be classified either by the control method of the water jet or by the diameter of the water jet (WB) as well as by the pressure of the water. Regarding the method of the water jet, they could be controlled by hand or remote controlled, both can be portable and self-moving. Also, they can be used for specific to close and long-ranged needs. In relation with the pressure of the water they can be classified as low, medium, high and super high pressured (See table 7). Low pressured hydraulic monitors are primarily used for tailings exploitation.

Figure 53. Hydraulic mining monitor (HR, 2019).

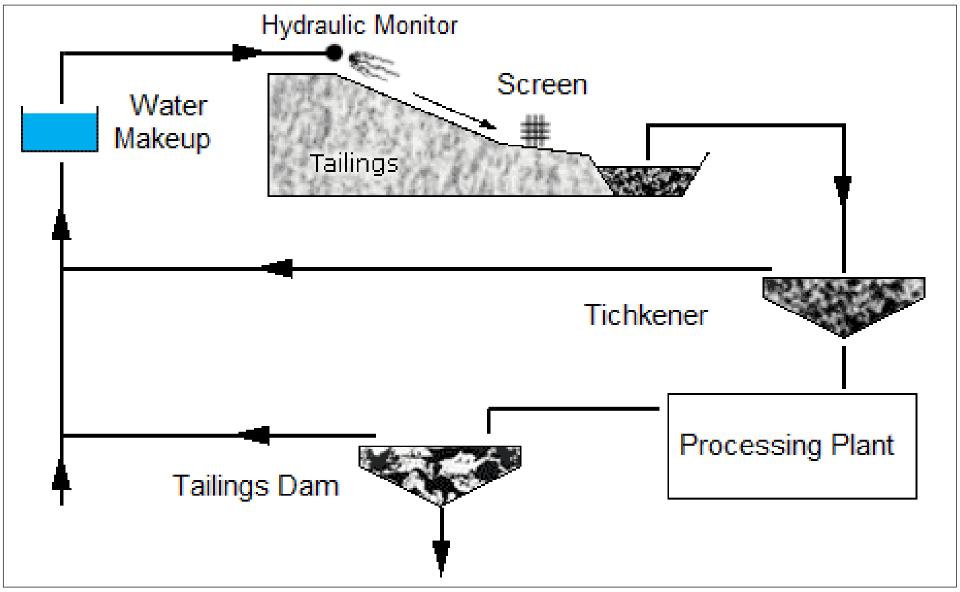

Figure 54. Hydraulic extraction of tailings (Engels, 2017).

Hydraulic monitor	Pressure (Pa)	Diameter of WB (mm)
Low pressured	$< 10^6$	50 - 150
Medium pressured	$10^6 – 6 \times 10^6$	15 - 30
High pressured	$6 \times 10^6 - 25 \times 10^6$	1 - 5
Super high pressured	25×10^7	< 1

Table 7. Hydraulic monitor pressure and diameters comparison (Engels, 2004).

Exploitation of tailings using hydraulic monitors has two main variations: exploitation from the top of the dam or exploitation from the bottom of the dam. In the first one, the monitors are placed on top of the material that is being evacuated and the slurry flows in the direction of the water jet in a special trench. The main advantages of this variation are that the monitor and pipeline system are placed on a dry surface, which allows to operate and carry them more simple. However, its main difficulty is that the water jet impacts into the material at a sharp angle (less than 90°), reducing the efficiency of the exploitation (See Figure 55). While, exploitation of tailings from the bottom is the most common method. It is considered more efficient because the water jet impacts into the material close to the optimal angle (90°), also this variation is less expensive because there is no need to prepare the area in detail previous to extraction. Nevertheless, the main disadvantages are associated with the difficult working conditions, security measures and constant monitoring of the flow path of the slurry to prevent migration and dam failures. In fact, for these reasons is recommended the implementation of remoted controlled hydraulic mining monitors (See Figure 56).

Exploitation of tailings by dry mechanical methods are less common than hydraulic mining methods, mainly due to economic, safety and environmental reasons. However, if the tailings dam fulfils all the necessary requirements, this method can be implemented. This method requires to dewater the tailings dam and eliminate open water tables before extraction operations start. The extraction technologies are usually based on exploiting, loading, and hauling of tailings using discontinuous or continuous mining equipment. However, the implementation of continuous technology is unlikely because their high dimensions and heaviness make them difficult to operate on a tailings dam. This is why discontinuous equipment has higher feasibility to operate on a tailings dam (Engels et al., 2004).

The most common discontinuous mining equipment used to extract tailings dams by dry mechanical methods is the single bucket dredgers (See Figure 57), this kind of machine has many variations, such as revolving excavators, slack line excavators, trencher excavators and grabbers. Furthermore, their different systems of transportation make them able to reach their point of operation such as wheels, walking drives, caterpillars, and can also by rails.

Figure 55. Hydraulic exploitation of tailings from the top (Engels, 2017).

Figure 56. Hydraulic exploitation of tailings from the bottom (Engels, 2017).

Figure 57. Single bucket dredgers variations (CAT, 2019).

5.2.7. Potential Projects

The Metalkol Roan Tailings Reclamation (RTR) Project located in the Democratic Republic of the Congo (DRC), is a comprehensive hydro-metallurgical facility to reprocess the historic tailings dumped into the environment from previous activities by other mining companies in the area in the 1950's. It belongs to the Eurasian Resources Group (ERG). RTR is considered a major tailings reprocessing operation and a low-cost hydro-metallurgical facility. The tailings dams that have been planned to be reprocessed by ERG contain copper and cobalt at an average grade of 1.49% and 0.32%, respectively, making these tailings dams economically viable to be recovered.

Metalkol Roan Tailings Reclamation project is considered the source of the world's largest cobalt producers at much lower cost. According to Eurasian Resources Group (2019), Metalkol RTR is nearing completion and is set to achieve the initial annual production rates of 14,000 tonnes of cobalt and 77,000 tonnes of copper in 2019. The Metalkol RTR project will set the production of the company about 350,000 tonnes annually of copper and more than 50,000 tonnes annually of cobalt (ERG, 2019).

O'Kiep & Carolusberg Copper Tailings is a future project owned by Xtract Resources focuses in reprocessing of two copper tailings dams located in the Northern Cape, South Africa. The project contains approximately 33.8 Million metric tons of sulphide tailings materials that were mined between 1980 and 2010, by the O'Kiep Copper Company. O'Kiep tailings dam represents 5.8 Million tonnes of material grading at 0.23% copper while Carolusberg dam represents 28 Million tons of material grading at 0.19% Cu. The company starts a drilling program on the tailings dams in order to define a measured and indicated resources and undertake metallurgical test work to determine mineralogy properties and recovery rates .

Renison Tailings Retreatment Project (Rentails) is located on the west coast of Tasmania, Australia. The objective of the Rentails Project is to reprocess the estimated of 22.5 million tonnes of tailings at an average grade of 0.44% tin and 0.23% copper from the historical Renison Mine, which is considered the largest tin producer in Australia and one of the few publicly held tin projects in the world. The current tailings dam has a probable ore reserve containing approximately 99,000 tonnes of tin and 51,000 tonnes of copper. It provides the opportunity to expand production at the Renison tin operations, by approximately 5,400 tonnes of tin and 2,200 tonnes of copper per year. Rentails is one of the largest single resources of tin available in Australia nowadays (Metals X, 2017).

There are other potential tailings dam retreatment projects like the reprocessing of the Morgan's tailings dam located in Australia and lead by the company Carbine Resources which estimates that more than one million ounces of gold have been left in the tailings from the Morgan mine. Another similar project is The Lagunas Gold Project, which is located in the Dominican Republic and belongs to PanTera Gold Limited and its main purpose is to reprocess previously unrecovered gold and silver refractory tailings dams. This project is expected to start its operation in 2019 (Ndlovu et al., 2017).

Tailings reprocessing industry appear to hold many advantages for the mining business, particularly because this practice reduces the risks associated with tailings dam failures because the waste that comes from the retreatment of tailings is placed in modern tailings storage facilities which have to meet the new geotechnical and environmental requirements which are much stringent that in the past.

6. LEGAL FRAMEWORK OF MINING WASTE MANAGEMENT

Mining activity in most of the cases like other economic activities, such as agriculture, forestry, chemical and engineering industries, banking, among others, is ruled through regulations and standards which vary from nation to nation and depends on local circumstances. Mining operation and environment protection requirements are most commonly implemented using different legal tools. For example, mining and environmental protection legislation as well as environmental planning and assessment legislation, and among other policies (BRGM, 2001).

The regulation that rules the mining industry has been changed over the years in order to improve the conditions of communities and the environment adjacent to mining projects. In most of the time, this transformation has been done in response to mining major accidents (Aznalcóllar, Spain in 1998; Baia Mare, Romania in 2000; Ajka, Hungary in 2010, Bento Rodriguez in 2015 and Brumadihno in 2019, both in Brazil) that have had catastrophic environmental and economic consequences. According to United Nation Environment Programme (2017), tailings dam failures are partly responsible of deficient mining legislation. The regulatory system has failed to ensure appropriate design of tailings dams that accomplish the necessary geotechnical and safety standards, and the implementation and monitoring of programs that guarantee the stability conditions of mine tailings storage facilities in the long-term.

The particular position of each country or government about the mining industry influences directly on the legislation that ruled the management of mining wastes, in combination with the potential impacts on the environment and communities, and also, it drives possible solution to this problematic. This situation makes necessary to develop technical solutions that meet high environmental standards without driving unrealistically high financial burdens on the business. In other words, it requires a legislation that is flexible enough and can adapt to particular conditions in order to propose specific solutions to different problematics (Allard et al., 2013).

The aim of this chapter is to present a brief summary of the mining waste legislation in industrialized countries, such as the United States of America, Australia, Chile, Canada, China and European Union, countries where the mining industry is considered an important economic activity.

6.1. Mining Waste Legislation in the European Union (EU)

Waste from extractive operations and mineral processing plants is one of the largest waste streams in the EU. It involves materials that must be removed to obtain access to the mineral resource which in most of the cases is considered worthless, like overburden and waste rock, topsoil, as well as tailings (EC, 2016). According to the European Commission (2019), the 2006/21/EC Directive (the Extractive Waste Directive) on the management of waste from the extractive industry is the basis for the majority of measures, procedures and guidance to prevent or reduce as far as possible any adverse effects on the environment and any resultant risks to human health, as a consequence of the poor management of waste from the extractive industries.

There are other important policies and legislations that fall under the regulation of the waste management framework of the European Union such as; The Best Available Techniques reference document for the management of tailings and waste-rock in mining activities, and the Seveso III Directive which includes in its scope operational tailings disposal facilities, including tailing ponds or dams, containing dangerous substances. Table 8 shows a compilation of the most relevant regulations and documents related to waste management from the mining and processing industry in the European Union (EC, 2019).

According to the Mine Waste Directive (EC, 2016), EU Member States must ensure that mining companies make and fallow a proper waste management plan with the objective to prevent or reduce the generation of waste and its negative impacts on the environment and communities, and to encourage waste recovery through recycling, reusing, reprocessing and land reclamation. Consequently, it is mandatory that every extractive waste management installation operates with a permit issued by the competent authorities, unless these installations contain non-hazardous waste from prospecting, unpolluted soil or solid or inert waste resulting from processing plants. Nevertheless, the way of implementing any new law or decree lick the 2006/21/EC Directive into national legislation varied from country to country. For example, in the case of the Baltic Sea Region (Germany, Sweden, Poland and Finland) except Norway approved and implemented the Directive 2006/21/EC (Allard et al., 2013).

Legislation	Description
Dir. 2006/21/EC	Directive on the management of waste from extractive industries
Dir.2010/75/EU	Directive on industrial emissions (integrated pollution prevention and control)
Dir. 2014/52/EU	Directive on the assessment of the effects of certain public and private projects on the environment (EU Environmental Impact Assessment (EIA) Directive)
Dir.2012/18/EU	Directive on the control of major-accident hazards involving dangerous substances
2009/335/EC	COMMISSION DECISION on technical guidelines for the establishment of the financial guarantee in accordance with Directive 2006/21/EC of the European Parliament and of the Council concerning the management of waste from extractive industries
2009/337/EC	COMMISSION DECISION on the definition of the criteria for the classification of waste facilities in accordance with Annex III of Directive 2006/21/EC of the European Parliament and of the Council concerning the management of waste from extractive industries
2009/360/EC	COMMISSION DECISION completing the technical requirements for waste characterization laid down by Directive 2006/21/EC of the European Parliament and of the Council on the management of waste from extractive industries
Methodological Guidance Note	Preparing a Waste Management Plan
Mine guidance	Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities

Table 8. European Commission Directives related with waste management from mining activity and processing plants (Politis et al., 2017).

6.2. Mining Waste Legislation in the United States of America (USA)

According to American Geosciences Institute (AGI) (2019), the United States of America mining industry is regulated at both federal and state levels. Determining which level of government has jurisdiction over mining activities largely depends on the surface and mineral ownership. At each level, regulation is achieved primarily through laws. The USA has been developing an extensive regulatory system for governing current mining operations, as well as to guide the rehabilitation or reclamation of historical ones (AGI, 2019).

The General Mining Law of 1872 (GML), governs the process for acquiring and maintaining a right to develop and extract locatable minerals from mineral deposits discovered on federal lands (US CONGRESS, 1872). Furthermore, there are other important laws that ruled, authorized and guided the mining industry in the United States of America which are exposed in table 9. In addition, each state has laws and regulations that mining companies must follow.

The principal regulatory agencies responsible for controlling the laws governing mining on federal lands in the United States of America are; the US Bureau of Land Management (BLM), the US Forest Service. Other important federal agencies that influence in mining regulation include the US Army Corps of Engineers and the Environmental Protection Agency (EPA). The last one is in charge to rule and regulated the waste produced by the mining and mineral processing industry (Fognani et al., 2018).

Legislation	Description
The Federal Land Policy and Management Act of 1976 (FLPMA)	Provides the legal framework within which mining rights acquired under the General Mining Law must be exercised in order to prevent undue and unnecessary degradation of federal lands
The National Environmental Policy Act (NEPA)	Requires federal agencies to evaluate the environmental impacts of major federal actions, including the permitting of mining activities on federal lands
The Federal Water Pollution Control Act (Clean Water Act)	Establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters
The Endangered Species Act	Established to protect and recover endangered and threatened species and their territory
The Comprehensive Environmental Response, Compensation and Liability Act (CERCLA)	Provides a Federal fund to clean up uncontrolled or abandoned hazardous-waste sites as well as accidents, spills, and other emergency releases of pollutants and contaminants into the environment
The US Bureau of Land Management (BLM)	The Bureau of Land Management's mission is to sustain the health, diversity, and productivity of the public lands for the use and enjoyment of present and future generations

Table 9. The United States of America general laws governing the mining industry and processing plants (Fognani et al., 2018).

6.3. Mining Waste Legislation in Australia

In Australia, the mining industry is governed by the Australian Mineral Industry Code for Environmental Management, sanctioned in 1996. This Code demands to every mining company to announce a public report each year about environmental subjects, such as; major incidents, prosecution, the position of the company with respect to environmental laws, decrees, permits, among others (BRGM, 2001).

According to Brennan et al (2013), each state and territory has its own legislation, which regulates the rights and duties for exploration and extraction of minerals. In addition, the Commonwealth powers under the Constitution incorporate topics that are relevant to mining projects. Another important legislatives policy governing mining in Australia is presented in Table 10.

Mining waste and tailings dams are matters generally included in environmental management plans submitted by mining companies to the State and Territory in order to have their approval. However, if tailings storage facilities are likely to have a major negative impact on the environment, mining projects may require approval from the Commonwealth Environment Minister under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). In addition, most of the States in Australia have their own legislation and particular requirements in relation to tailings facility design and operation (ICLG, 2019; Brennan et al., 2013).

Legislation	Jurisdiction
Planning and Development Act 2007	Australian Capital Territory
Offshore Minerals Act 1994	Continental Shale and Exclusive Economic Zone
Mineral Titles Act 2010	Northern Territory
Offshore Minerals Act 1999 and Mining Act 1992	New South Wales
Offshore Minerals Act 1998 and Mineral Resources Act 1989	Queensland
Offshore Minerals Act 2000 and Mining Act 1971	South Australia
Mineral Resources Development Act 1995	Tasmania

Table 10. Australia general laws governing mining (ICLG, 2019a).

6.4. Mining Waste Legislation in Chile

In Chile, the exploration and exploitation of natural resources contribute to an important share of the country's gross domestic product (GDP) and is a great source of foreign investment. The most important mineral resources in Chile are: copper, molybdenum, silver and gold. In this country, the regulatory framework governing the mining of mineral resources is based on The Political Constitution of the Republic of Chile, which provides the legal basis for mining legislation (Dossantos, 2018). Nevertheless, there are other important laws or decrees that regulate the mining activity, which are exposed in Table 11.

In Chile, the institutions that administer the mining industry are; The Ministry of Mining which its mission is to lead the development of public policies and laws in order to increase the participation of the mining industry in the national development. Additionally, there is the National Geology and Mining Service (SERNAGEOMIN) which is in charge to approve technical and safety matters of mining projects and supervises their achievement (SERNAGEOMIN, 2019).

Decree No. 248, states that; with respects to approval, design, construction, operation and closure of tailings dams declares that for the construction of any kind of tailings storage facilities consent from SERNAGEOMING is compulsory. In addition, an approval from the General Water Bureau is mandatory when a tailings dam has a capacity of 5000 m^3 or more (Ministerio de Mineria, 2007).

Legislation	Description
The Organic Constitutional Law on Mining Concessions	Describes the general terms of mining concessions
The Chilean Mining Code	Emphasizes the procedures of how to gain exploration and exploitation concessions
The Mining Code Regulations	Reinforces the Mining Code
The Mining Safety Regulation	Deals with the safety of the workers involved

Table 11. Chilean general laws governing mining (SERNAGEOMIN, 2019).

6.5. Mining Waste Legislation in China

In China, the national law that rules the mining industry is The Mineral Resources Law (MRL), which was promulgated by the Standing Committee of the National People's Congress in 1986, and amended in 1996 and 2009, respectively. Furthermore, there are other important regulations which influences the mining business in china, which are presented in Table 12. The most important agencies that govern the mining industry in China are: The Ministry of Natural Resources (MNR) and its local's bureaus along with other departments and ministries that regulate others issues related to the mining industry. For example, the Ministry of Ecology and Environment (MEE) and the Ministry of Commerce (ICLG, 2019b).

According to Wu et al (2018), the Government of China implemented a Restoration Fund system (RFS) in 2017, which states that the holder of mining rights may use the fund at his owns discretion in order to design and formulate plans for land reclamation and also for tailings dam management. The above, according with a previous Environmental Impact Assessment (EIA) approved by the Ministry of Ecology and Environment (MEE). The RFS, was made in order to give mining companies more autonomy on how to use the funds and at the same time to reduce their financial burdens.

Legislation
Rules for Implementation of the Mineral Resources Law 1994
Administrative Measures for the Block Registration of Mineral Resource Prospecting 2014
Circular of the Ministry of Land and Resources on Further Regulating the Administration of the Approval and Registration of Mineral Resources Exploration 2017
Administrative Measures for the Registration of Mineral Resources Exploitation 2014
Provisions on Administration of Mineral Resources Compensation Collection 1997
Measures for the Preparation and Implementation of Mineral Resource Plans 2012
Measures for the Administration of Transfer of Mineral Exploration Rights and Mining Rights 2014

Table 12. Chinese general laws governing mining (Wu et al., 2018).

7. ANALYSIS OF THE INFORMATION AND DISCUSSION

The literature review that has been presented in this study demonstrates that the consumption and exploitation of mineral resources have considerably increased in the last decades, mainly because of the intense population growth, the decreasing of some metal ore grades, the expansion of urban areas and economic improvement of developing countries which implies to cover the basic needs that arise. Unfortunately, the inflation in demand and the dependence on mining to produce large amounts of these essential natural resources has occasioned the processing of high volumes of mineralized material that subsequently results in the coordinated production of a significant volume of mine wastes, specifically mine tailings which it is known to be a global problem for all stakeholders involve in the mining business.

Communities and ecosystems settle down near to the mining projects feel much more the negative impacts associated with mining wastes. Tailings dams are main contributors to the numerous environmental problems. Air and soil can be contaminated by the generation and dispersion of dust from tailings dam. Water sources can be polluted by seepage of mining waste embankments that are more likely to generate acid mine drainage due to their contact with potential substances in the environment. Most dramatically, tailings dams can fail, resulting in severe and sometimes catastrophic consequences.

Although environmental and social impacts are the most important concerns for the media and scientists. The economic, statutory and political problems of management of mining waste are key matters for the mining industry. In relation to economics, mining companies have to design and plan alternatives to dispose, storage and monitor mining waste at high cost without revenues. Statutory, the companies need to fulfill many technical and environmental legislative requirements necessary for the construction of tailings storage facilities which every year has become stringent, a situation that is more evident in developed countries. Additionally, political issues can be originated by transboundary migration of effluent in rivers or lands which sometimes take place in tailings dam failures. For example, the Baia Mare and Baia Borsa incidents in Romania, in 2000, that affected Hungary and the former Yugoslavia, this tailings dam failure could have resulted in a diplomatic transboundary problem.

Conventional tailings dams are the most common form of waste disposal. However, they represent a high potential risk in mining operations in terms of geotechnical and environmental stability. Statistical data compiled, analyzed and presented in this research demonstrates that, on average, there was at least one mine tailings incident documented each year between 1965 and 2019. In fact, some of these tailings dam failures have been classified as mining major catastrophes, as was the case of Brumadinho dam disaster, in Brazil, 2019, which happened at the time of writing this thesis. This current gap associates with proper management of mine tailings is addressed by this study. Particularly by exploring and highlighting different sustainable tailings disposal options.

The sustainability of mine tailings disposal options has been studied for many researchers during several years. Indeed, this investigation tried to explore the possibility of reusing, recycling or reprocessing tailings dams through characterization of their technical parameters, such as, grain size distribution, specific gravity, Atterberg limits, natural water content, consolidation coefficient, hydraulic conductivity, among others, by collecting and analyzing an extensive bibliography regarding tailings dam properties from different ore mines worldwide. Unfortunately, as Lottermoser and many other authors agree, one major difficulty concerning reuse and recycling of mine waste is the quantification and distribution of elements and minerals in all scales as well as in space and time in mining wastes. There is an urgent need for developing methods that allow to assess and evaluate the physic, geochemists and mineralogical properties of mining waste in order to understand their long-term behavior. The lack of data in this specific area is one of the major challenges to determine the real potential of reuse, recycling and reprocessing of mine tailings dams (Lottermoser, 2010; Lottermoser, 2011; Bellenfant et al., 2013).

This research studied the literature cautiously in order to identify and recommend sustainable alternatives for reuse, recycling and reprocessing of mine wastes, especially mine tailings, considering economic, technical, environmental and social characteristics. Looking at mine wastes as an opportunity for developing new potential solutions that encourage the total resource utilization and the possible accomplishment of zero waste which is the optimal and idyllic solution for successful mine waste treatment and their disposal in the long term.

The review and information presented in this research indicate that there are many applications for the utilization of mine wastes. For example, use of tailings in the elaboration of bricks, aggregate in concrete, stone paper making, extenders in paint, for the production of tiles and glass ceramic products, among others. It could be a sustainable economic, technical and environmental solution to the problem of mine tailings dams. These practices could guarantee the implementation of the large amount of mine wastes in order to considerably decrease their quantity in the environment or in the best of the case to eliminate them completely. Additionally, several examples of existing solutions for the mining industry about tailings dams reprocessing, which enable improved total resource efficiency and metal extraction were identified and presented.

Many researchers agree that reuse, recycling and reprocessing of abandoned or active tailings storage facilities can create shared value between mining companies, communities and the environment. In the mining business wise, the companies reduce the costs associated with tailings dam disposal, treatment, monitoring and land reclamation and at the same time can bring profit to the organization. In addition, mining firms accomplish with stringent environmental legislation and reduce the risk of penalties associated with mine waste accumulation. Finally, the reputation and perception of the mining industry can be improved to simplify the achievement of social license, which is increasingly important and essential to approve new mining projects and ensure the continuity of those that currently exist.

Regarding community and environmental wise, reuse, recycling and reprocessing of mine waste, encourage innovation, develop local industry and generate jobs. Advances in processing technology allows recuperation of minerals from historical mining and mineral processing wastes that were abandoned in the past and were considered useless, improving in this way the sustainable consumption of natural resources, slowing their depletion and preserving the non-renewable mineral resources for future generations. Finally, reuse and recycling of mine tailings dams limit and reduce waste production decreasing the exposition of humans and ecological receptors to hazards and polluted materials, such dam failures, generation of acid mine drainage, exposition to heavy and toxic metals, among others important hazards.

Although much research has been conducted on the development of new methods and technology for reutilization, recycling and reprocessing of mine waste, especially mine tailings, its application is still very limited due to the following possible reasons; first of all, most of the suggested methods for mine waste management require high capital investment. Secondly, the lack of relevant standards and government policies that promote innovation and long-term sustainable solutions. Finally, nonexistence public acceptance and education regarding reuse and recycling of mine tailings. Unfortunately, these potential solutions for mine waste management have remained ideas or laboratory trials without wider application. These ideas have not been taken up by industry because at the end they are driven by their practical applications and financial returns (Zhang, 2013).

The production and consumption of mineral commodities are well documented by mining companies and governments. There are many public and private agencies in charge to collect and distribute this information. Nevertheless, there is no precise data available about the global production of mine wastes. This research addressed this gap and estimated the mine solid waste annual worldwide production, particularly the generation of mine tailings of five mineral commodities with the highest demand in the market, such as copper, gold, iron ore, bauxite and coal. It was led by reviewing and analyzing some assumptions regarding mineral extraction and processing plant waste generation suggested by different authors, especially by Lottermoser.

This investigation found that the production of solid mine waste annually is superior to 30 billion metric tons worldwide and at least 7 billion of these tonnes are considered mine tailings. It means that mine tailings represent at least 25% of the total mine waste generated in the world. Additionally, this study estimated that the global solid waste production of copper has increased at least 1 billion tonne from 2010 to 2017, when around 4 billion of copper mine solid waste were produced, and 1 billion corresponded to mine tailings. In the same year, more than 1.5 billion tonnes of gold mining solid waste were generated worldwide and around 400 Million tonnes were mine tailings. Furthermore, the total production of bauxite solid mine waste reached almost 300 million metric tons, of which 70 million tonnes were considered mine tailings, in 2017.

In 2017, the generation of iron solid mining waste in the world was about 2.5 billion tonnes. In the same year the production of iron mine tailings was about 600 million metric tons. Finally, this research found that in 2017, approximately 7.3 Billion metric tons of solid waste were produced by the coal industry and at least 1.8 billion metric tons were mine tailings. However, this statistic showed that the production of coal mining waste decreased in almost 500 million tonnes from 2013, it could be the results of the reduction of coal production and consumption due to environmental policies and promotion of different kinds of renewable energy.

This research studied briefly the legal framework of mining waste management in different countries. It found that many researchers believe that most of the mining and environmental policies are hampering innovation to reuse, recycle and reprocessing mining wastes instead of promoting it. First of all, mining policy is considered excessively general, while problems associated with mining wastes are very specific; their potential impacts and solutions vary from site to site, which requires a legislation that is flexible enough and can adapt to the particular conditions in order to propose specific technical solutions that meet high environmental standards but without driving unrealistically high financial burdens on the business. Secondly, the process of mining waste recovery is not categorized as preparation for reuse and recycling, which makes the extractive industry no eligible to receive public funds. Third, frequently the storage of the mining waste at the mine site is free of charge. As a result, mining companies are not motivated to find different techniques to manage the waste generate. Finally, the procedure for obtaining permits to reuse and recycle mining waste is often complicated, time-consuming and expensive. In the end, it turns out much economical and easy to use materials from natural resources which come from their producers. All these circumstances are factors holding back mining companies to develop innovative and sustainable solutions regarding the problem of mining waste management (Allard et al., 2013).

8. CONCLUSIONS

Mining and mineral beneficiation processes produce more than 30 billion tonnes of solid mine waste and at least 7 billion tonnes of mine tailings worldwide annually. Furthermore, as population as well as demand for minerals and metals increase, and ore grade deposits decrease, the global production of tailings is projected to keep growing. Hence, tailings dams are main contributors to many environmental problems. The consequences of tailings dam failures throughout the history have been economic losses, environmental pollution, and in the worst cases, human loss. Then, the problematic of mine tailings dams is an important global concern. The main conclusion to be drawn from this review, therefore, is that tailings should be reused or recycled in order to encourage the possible accomplishment of zero waste which is the idyllic solution for effective management of mine waste in the long term.

Reuse, recycling and reprocessing of abandoned or active tailings dams create shared value between mining companies, communities and the environment. Nevertheless, it is difficult to determine a common and global method for total reutilization of mine tailings. However, each tailings dam depending on its mineralogical, geotechnical, physical and economic characteristics can be reused. The information collected and analyzed by this research indicates that there is a lack of appropriate and current techniques that promote sustainable development of mine tailings, a situation that is an important challenge for the mining industry.

The currently available legal framework associated with mine tailings management is limited and its application considered excessively general. A mine tailings legislation flexible enough and adjustable to particular conditions which promotes and facilitates innovation to reuse and recycle mine wastes instead of hampering and driving high financial burdens on the business is needed.

Finally, it is recommended to encourage more research on the potential industrial applications of mine tailings, so that their volume can be reduced and at the same time the exposition of humans and ecological receptors to any source of hazard related to mine tailings. Furthermore, it provides mining companies with the opportunity to have incomes and to prove environmental and social management commitments.

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10. LIST OF FIGURES

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