POLITECNICO DI TORINO

Master Degree course in Georesources and Geoenergy Engineering

Master Degree Thesis

Technical and Environmental Considerations for Valorisation of Mine Tailings

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All glory and honor to the Almighty God, whose grace and blessings have guided me every step of the way.

Abstract

This thesis explores the valorisation of copper mine tailings, aiming to transform this waste material into valuable secondary resources. The study focuses on recovering residual minerals and converting tailings into commercially viable ceramics, bricks, and geopolymers. Techniques, such as flotation, and bioleaching, are evaluated for their potential to recover copper, with recovery rates ranging from 57% to 74%, depending on the methodology applied. The technical feasibility and scalability of different valorisation processes are assessed for several case studies. The study demonstrates the potential for tailings reprocessing to contribute to resource efficiency by recovering valuable minerals and creating secondary products that partially replace primary raw materials.

A life cycle assessment (LCA) framework is employed to evaluate the environmental impacts of reprocessing copper tailings. The results highlight significant potential for reducing greenhouse gas (GHG) emissions by substituting primary materials with products derived from tailings, such as ceramics and CSA cement. Environmental comparisons between conventional copper processing methods, and tailings reprocessing routes show that reprocessing reduces GHG emissions and addresses other environmental challenges, such as heavy metal contamination and ecotoxicity risks. To achieve the highest CO_2 savings, it is essential to focus on displacing coal-fired electricity in ceramics production, particularly in countries that rely heavily on coal. This approach could result in savings of up to 21 million tonnes of CO_2eq by 2050.

However, challenges remain, particularly in managing the energy demands and environmental impacts associated with secondary metal recovery processes, which can contribute to freshwater ecotoxicity and other environmental burdens. These findings underline the importance of optimizing energy use, particularly in energy-intensive stages like metal recovery, to enhance the overall sustainability of tailings valorisation.

In conclusion, this research underscores the importance of copper tailings valorisation as a strategy for reducing waste and mitigating the environmental impacts of mining. Although the recovery of valuable products has significant environmental benefits, the high energy requirements of some processes require further optimization. It is recommended that future work focus on improving the efficiency of metal recovery techniques and exploring innovative approaches to minimize energy consumption and environmental harm. More attention should be given to scaling up these processes and integrating them into broader sustainable mining practices.

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Chapter 1

Introduction

1.1 Background and Context

1.1.1 The Global Mining Industry and Its Strategic Importance

Mining has always played an important part in human civilization since the dawn of time, providing essential raw materials that have accelerated advancements in technology, infrastructure, manufacturing, construction, and other industries. The mining sector is also a major economic driver, significantly contributing to the Gross Domestic Product (GDP) of many countries. It provides employment for millions of people, supporting entire communities and promoting economic stability Atlas [2016].

1.1.2 Developing Countries

In developing nations, mining sometimes catalyses economic growth, attracting substantial investment from developed countries and offering a pathway for infrastructure development and community upliftment. The industry's contribution extends beyond economics, as it also plays a pivotal role in achieving the United Nations Sustainable Development Goals (SDGs). Some SDGs achievable through mining are (SDG 8: Decent Work and Economic Growth) and infrastructure development (SDG 9: Industry, Innovation, and Infrastructure). As highlighted in the Mapping Mining to the Sustainable Development Goals Atlas [2016] by the United Nations Development Programme (UNDP), Mining has the potential to contribute to all 17 SDGs.

1.1.3 European Union

Within the European Union (EU), the mining industry is a driving force behind economic stability and development. The EU has identified a critical list of strategic minerals vital for maintaining its economic strength and ensuring the continued development of its key industrial sectors. Many strategic minerals, such as copper, cobalt, and other base metals, are obtained through mining and are important to the EU's economy . The increasing global demand for these raw materials, driven by the need to advance green technologies, electric vehicles, and renewable energy infrastructure, has further highlighted the importance of these minerals Sprott [2024]. As a result, there has been a significant surge in the production of copper and other base metals in regions with rich mineral deposits, highlighting the global relevance of these resources in maintaining the EU's industrial competitiveness and supporting its transition to a sustainable economy.

1.2 Generation of Mine Tailings

The extraction of economically valuable minerals from the earth always leads to the generation of mine tailings, a byproduct of the mineral separation process. Minerals of economic value are often interlocked with waste material or exist in low concentrations that are not economically feasible to extract without significant processing. To recover these valuable minerals from the ore, various processing techniques are employed to liberate the minerals and separate them from the waste material. These separation processes can either be physical for example, density separation or chemical like cyanidation, flotation. These processes require that the ore be reduced to a fine size by comminution to ensure that even the smallest mineral grains are freed. The waste materials produced from these processes are known as tailings, which are usually a mixture of finely ground rock, water, and residual processing chemicals. These tailings represent a significant environmental challenge due to their volume, composition, and the potential for environmental contamination.

1.2.1 Environmental Implications

Technological advancements in mining have enabled the extraction of large volumes of ore using highly productive equipment. This technological progress has made it feasible to mine low-grade ores previously uneconomical some decades ago. While this has undoubtedly increased resource availability and extended the lifespan of mining operations, it has also led to the generation of vast quantities of waste. The large-scale extraction of low-grade ores produce huge volumes of tailings, contributing to land degradation, environmental pollution, and the destabilization of ecosystems. Globally, billions of tons of tailings are produced annually, forming man-made mountains that are eyesores and also potential sources of environmental hazards. These tailings pose significant risks, including contaminating various water sources through acid mine drainage and the releasing toxic heavy metals into the environment.

1.2.2 Economic Implications

The economic implications are also significant. The costs associated with the management, storage, and remediation of tailings are quite substantial. The presence of residual valuable minerals in tailings is an opportunity to reprocess these huge dumps, which, if applied correctly, could offset some of the environmental and economic costs associated with tailings management.

1.3 Problem Statement

1.3.1 Copper Production

The global copper mining industry, particularly in copper-rich regions such as Chile, Peru and the Democratic Republic of Congo (DRC), has experienced a significant increase in production, rising from 16 million metric tonnes in 2010 to 22 million metric tonnes in 2023, according to Statista [2024a] shown in Figure 1.1. This growth has been driven by the increasing demand for copper worldwide, a trend expected to continue in the coming years.

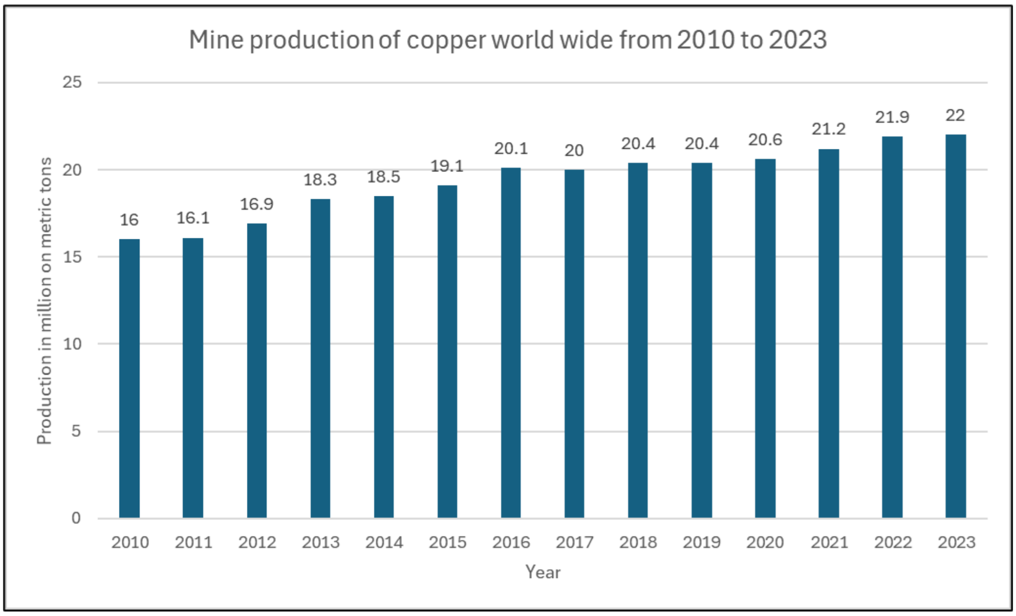


Figure 1.1. Production of Mined Copper worldwide 2010 to 2023 Statista [2024a]

1.3.2 Copper Production Forecast

According to [IWCC], global demand for copper is forecasted to rise even further in 2024 and 2025, putting additional pressure on the mining industry to meet this demand. The trends are summarised in the Figure 1.2. The sharp decrease in Africa may be attributed to Egypt which has been undergoing significant infrastructure development, including large-scale construction, energy projects, and industrial expansion in the past recent years. These projects are estimated to reach completion towards the end of 2024. This might result in the demand for copper used in wiring, electrical systems, and machinery drastically declining.

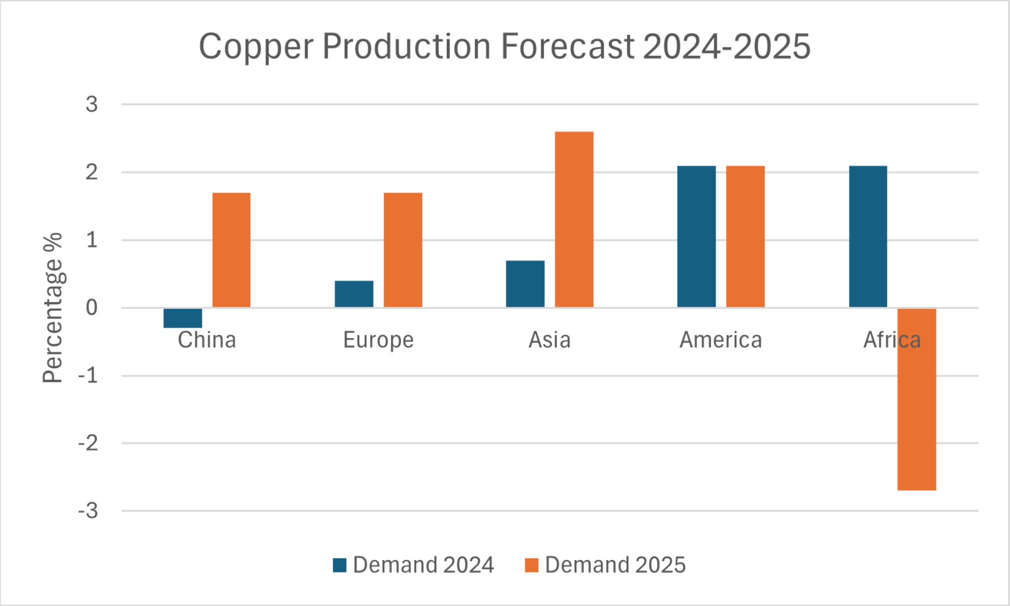


Figure 1.2. Copper Production Forecast for 2024 and 2025 [IWCC]

1.3.3 Copper Tailings Production

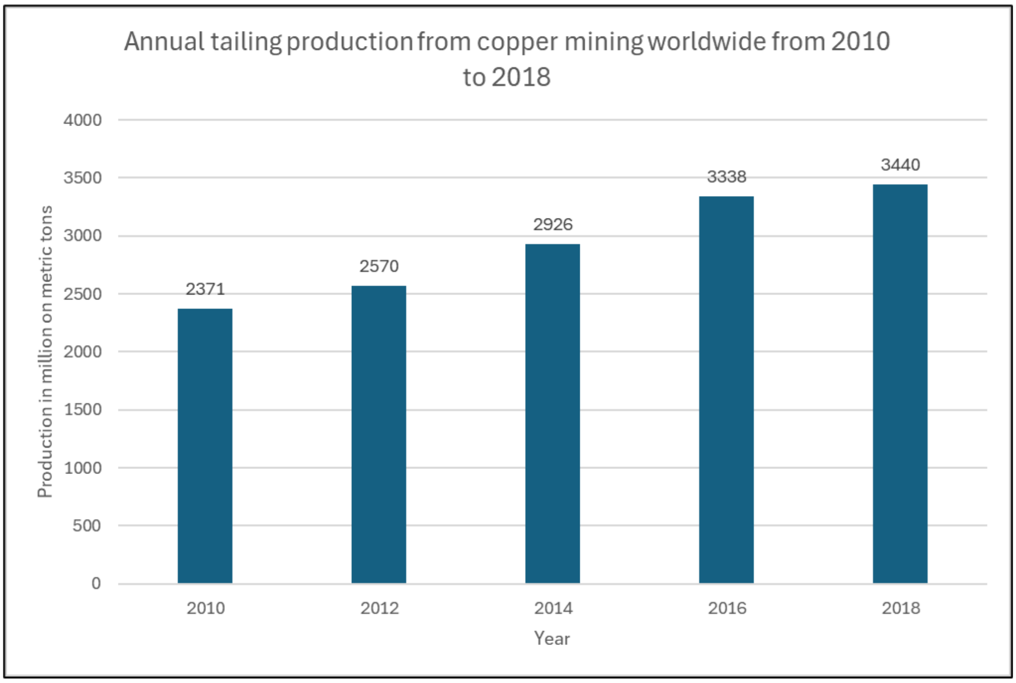


Figure 1.3. Annual tailing production from copper mining worldwide from 2010–2018 Statista [2024b]

This surge in copper production has led to a corresponding increase in the generation of mine tailings as shown in Figure 1.3. According to Statista [2024b], the volume of copper tailings reached 3.44 billion metric tonnes, up from 3.34 billion metric tonnes in 2016. This highlights a worrying trend. If current mining practices continue, the volumes of tailings generated will only rise, worsening the environmental challenges associated with their storage and management. Despite numerous efforts to improve in waste management practices, most copper tailings are stored indefinitely, leading to potential environmental risks such as soil and water contamination. Moreover, the underutilization of valuable secondary resources within tailings, such as residual copper, represents a missed opportunity for resource recovery

1.4 Research Focus

The valorisation of copper tailings through the recovery of residual metals followed by converting the inert material into useful products such as cement or polymers offers a promising solution to these issues. Yet, the technical feasibility and environmental sustainability of such approaches remain underexplored. This thesis aims to investigate these aspects, focusing on the potential for valorisation of copper tailings to reduce environmental impacts and contribute to more sustainable mining practices.

1.5 Objectives of the Study

The study seeks to identify opportunities for the effective reuse and transformation of copper tailings into commercially viable products, such as cement and polymers. Additional specific objectives include:

i. **Assess the Technical Feasibility of Tailings Conversion**

   This study aims to evaluate the technical processes involved in converting copper mine tailings into valuable products. The goal is to determine the most efficient, and sustainable methods for tailings conversion, focusing on the technical scalability and industrial readiness for large-scale implementation.

ii. **Conduct a Comprehensive Life Cycle Assessment (LCA)**

   A key objective of the study is to conduct an LCA to quantify and compare the environmental impacts of large-scale copper tailings valorisation. This includes assessing energy consumption, emissions, resource efficiency, and environmental trade-offs when valorising tailings versus traditional disposal methods.

1.6 Scope of the Study

1.6.1 Geographical Focus

This investigation will primarily focus on copper-producing regions that are significant contributors to global copper production. These include Chile, Peru, the Democratic Republic of Congo (DRC), and China, according to their production, from the highest to the lowest producer. These regions are chosen due to their large-scale copper mining operations and the associated challenges of tailings management. The methodologies and results of the investigations may be of relevance to other copper-producing nations.

1.6.2 Technical Feasibility

The study will evaluate the technical processes involved in valorising copper mine tailings. This includes analysing methods for recovering residual copper and other valuable minerals from sulfidic copper tailings. It will also focus on converting tailings into commercially viable industrial products, such as cement or polymers and lastly, assessing the infrastructure, technologies, and industry readiness for implementing these processes at a large scale.

1.6.3 Environmental Sustainability

The environmental impact of tailings valorisation will be assessed using Life Cycle Assessment (LCA). This involves evaluating the potential reduction in environmental risks associated with tailings storage against valorisation process. The study will also explore the resources required for valorisation of copper tailing, such as energy and water usage, and the emissions generated during the process. A comparative assessment will be conducted to evaluate the environmental performance of valorisation processes versus conventional copper processing methods currently being used.

1.6.4 Exclusions

This study will not include a detailed analysis of tailings from non-copper mining industries, although general references may be made to highlight similarities or differences. It will not include the evaluation of the economic viability of tailings valorisation.

1.7 Significance of the Study

This study has the potential to make a significant contribution to the field of mine tailings management. This research could serve as a template for similar efforts in sulfidic tailings. The findings may lead to more sustainable practices and influence the development of global policies related to mining waste management. Moreover, the successful valorisation of tailings could significantly advance the concept of a circular economy within the mining sector. By transforming waste into valuable resources, this study highlights the potential for reducing environmental impacts while creating new economic opportunities.

Chapter 2

Literature Review

2.1 General Overview of Copper Mining

2.1.1 Mineralogy

Copper is a non-ferrous base metal with an average concentration of about 50 ppm in the Earth's crust. The minimum exploitable grade for copper deposits is typically around 0.4% Bide et al. [2009]. Copper minerals can be categorized into three main groups:

i. **Primary (Hypogene) Minerals**

   These are associated with hydrothermal processes and include bornite, chalcopyrite, and enargite.

ii. **Copper Oxides**

   Formed through the weathering of copper sulphides, examples include cuprite, malachite, chrysocolla, and covellite.

iii. **Secondary Sulphides**

   These include chalcocite and covellite, formed from the leaching of near-surface sulphides. Disseminated Copper Sulphide Deposits dominate global copper production. Approximately 90% of copper is derived from sulfide deposits, with chalcopyrite accounting for about half of global copper output Bide et al. [2009].

Major Copper Deposit Types

1. Porphyry Copper Deposits: These are the most significant source of copper, contributing 50 to 60% of the world's production. They also supply molybdenum (99% of global production), rhenium, and other by-products like gold, silver, and tin Bide et al. [2009].

2. Sediment-Hosted Copper Deposits: These deposits account for approximately 20% of global copper production Bide et al. [2009]. They are also primary sources of cobalt, especially in the Central African Copperbelt. The recovery of these by-products not only contributes to the economic viability of mining projects but also supports the circular economy by minimizing waste and maximizing resource utilization

2.1.2 Production Routes

Mining

Copper ore is extracted using the following principal methods:

i. **Open-Pit Mining**

This method is most common for near-surface, lower-grade ore bodies like porphyry copper and skarn deposits. Large-scale operations, such as the Bingham Canyon Mine in Utah, extract chalcopyrite and bornite using explosives, with the ore then transported for further processing Bide et al. [2009].

ii. **Underground Mining**

This method is applied to deeper and higher-grade deposits, depending on the orientation of the mineral deposit, various techniques are used. These include block caving, room and pillar, and stoping methods Bide et al. [2009].

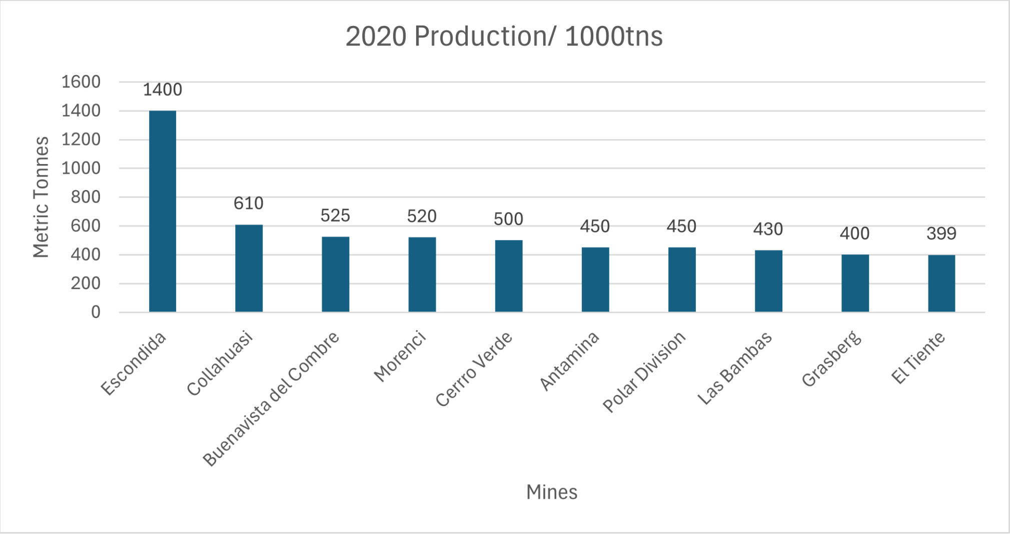


Figure 2.1. World's 10 largest Mines ICSG [2020]

As of 2020, the top 10 highest-producing mines were primarily located in the Americas, specifically in countries like Chile, Peru, Mexico and the United States. Of these 10 mines shown in Figure 2.1, only one is an underground mines called Grasberg mine in Indonesia. The other nine are large-scale surface mines. This further highlights the dominance of surface mining in the copper industry, as these mines can move substantial volumes of ore and waste ICSG [2020]

Processing

Pyrometallurgical Processing

Pyrometallurgy is the primary process for copper concentrate refining. The copper is roasted, smelted, and converted through the following stages:

i. Roasting, whereby copper concentrate is partially oxidized.

ii. Smelting, where the copper is further separated from impurities.

iii. Converting, where copper is purified into matte (35-68% Cu), and blister copper (97-99% Cu) Bide et al. [2009].

iv. Fire Refining and Electrolytic Refining, which is further purification of blister copper.

Hydrometallurgical Processing

Hydrometallurgy involves the chemical or biological leaching of copper from ores using dilute sulfuric acid, with subsequent concentration via solvent extraction and electrowinning. This process is energy efficient.

Recycling

Copper recycling accounts for two-thirds of total copper production. Producing copper through recycling is about six times more energy-efficient than primary production. Recycling processes vary based on the purity of the scrap. High-purity scrap such as slag and fines are re-melted for reuse, while less pure scrap such as end of life vehicles and electrical equipment is mixed with fresh copper or electrolytically refined.

2.2 Global Copper Production trends

From 2010 to 2023, global copper production increased by approximately 30%, reaching 22 million metric tonnes in 2023. This significant growth is driven by rising demand for copper in various industries, including electronics, construction, and renewable energy technologies. According to data from Statista [2024a], global copper reserves are estimated to be around 1 billion metric tonnes as of 2023. The largest copper-producing nations include Chile, Peru, Democratic Republic of Congo (DRC), China, and the United States. Among the leading mining companies, Freeport-McMoRan is the top producer, exceeding 2 million metric tonnes annually, followed by BHP which produces 1.39 million metric tonnes.

2.2.1 Chile Production

Chile is the world's largest copper producer, contributing a significant portion to the global supply. Copper mining accounts for approximately 10% of Chile's GDP, with over 50% of the country's exports directly related to copper sales. Chile is also a key recipient of foreign direct investment (FDI), primarily due to its vast copper reserves and mining infrastructure Urrutia et al. [2017]. The largest copper production companies in Chile are Corporacion Nacional del Cobre de Chile (Codelco) and BHP, which together produced half of the country's total copper output in 2022. Other notable companies, such as Anglo American and Rio Tinto, also play important roles in the sector, contributing to Chile's global dominance in copper production as shown in Figure 2.2.

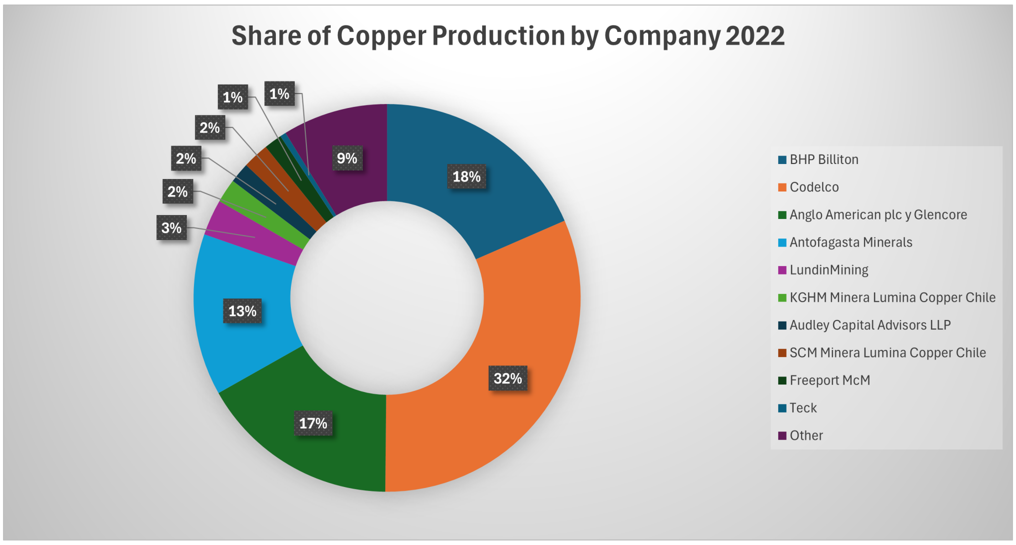


Figure 2.2. Share of copper production by company Commission [2017b]

Evolution of Copper Production in Chile

Chile is home to around 21% of the world's copper reserves despite covering only 0.6% of the Earth's land surface. Copper production has played a fundamental role in Chile's economic growth, transforming it into a global mining powerhouse. From producing 1,600 metric tonnes of copper in 1990, the country saw an increase to 5,325 metric tonnes by 2022 as shown in Figure 2.3. The steady rise in production reflects the importance of copper to Chile's development. Chile's copper production peaked in 2004, reaching 5,413 metric tonnes. Since then, output has fluctuated slightly, but production levels have remained close to the 2004 peak. Much of this production can be attributed to the private sector, which has significantly driven copper output in the country.

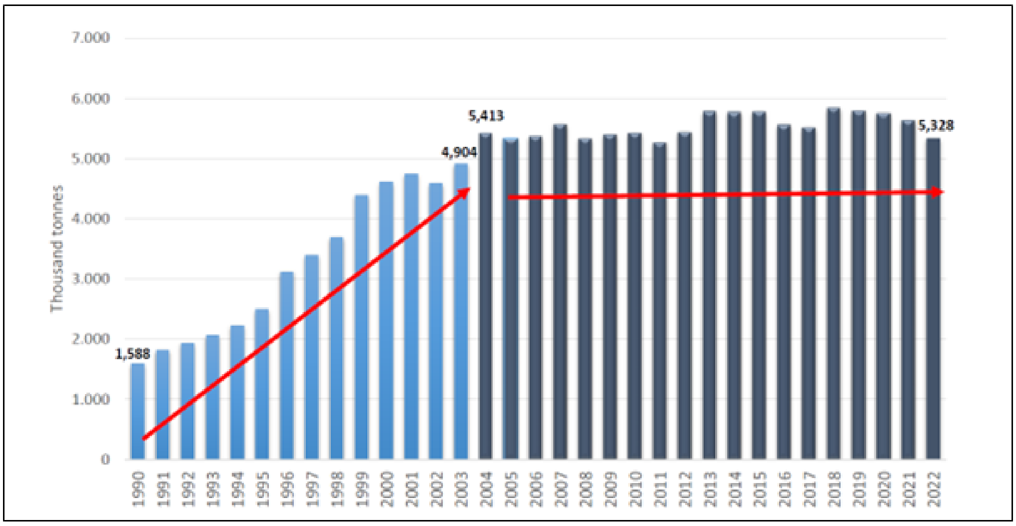


Figure 2.3. Country’s Copper Production Valdivieso [2023]

Private Sector Copper Production

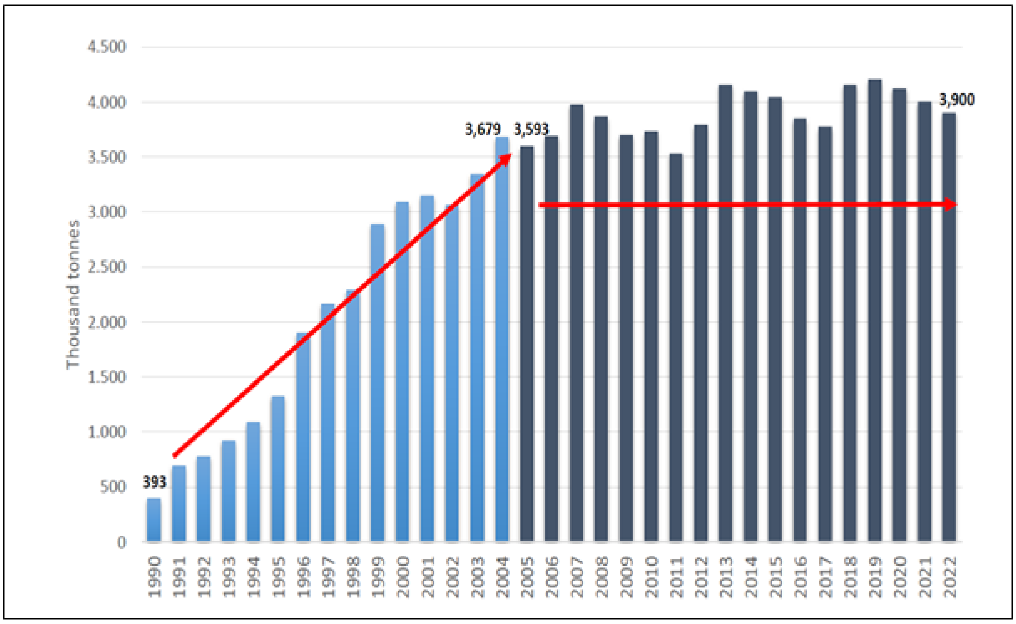


Figure 2.4. Private Copper Production Valdivieso [2023]

The private sector in Chile has been a major force behind copper production. In 1990, private companies accounted for just 24.7% of total copper production Valdivieso [2023]. However, by 2004, private sector contributions rose sharply to 67.9%, as shown in Figure 2.4, highlighting the role of direct foreign investment in the copper mining industry.

The growth of the private sector continues to support copper production in Chile, attracting significant foreign investment and expanding export opportunities.

Economic Impact of Copper Mining in Chile

Copper mining has significantly shaped Chile's economic landscape. The sector has contributed to increased foreign investment, boosted GDP growth, and expanded export markets. Below is an overview of key economic indicators related to copper mining:

i. According to Valdivieso [2023] Mining exports increased from \$10 billion USD in 1990 to \$60 billion USD by 2022. Copper represents a major share, contributing 61.9% of Chile's total exports.

ii. Chile's Gross Domestic Product (GDP) surged from \$62 billion USD in 1990 to \$312 billion USD in 2022. This impressive growth underscores the importance of copper to Chile's economy as shown in Figure 2.5.

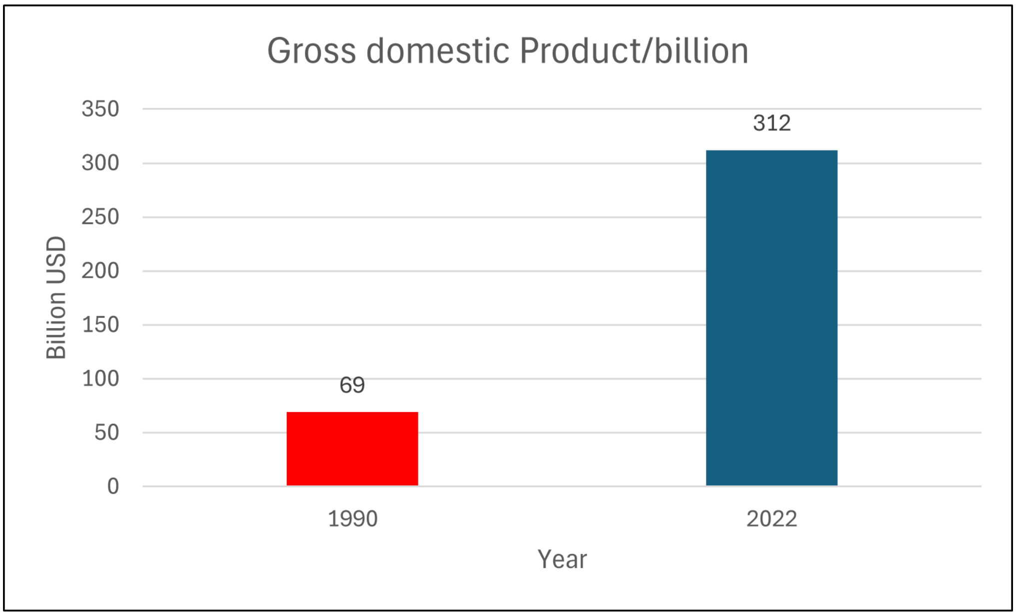


Figure 2.5. Chile's GDP Valdivieso [2023]

iii. Chile's GDP per capita shown in Figure 2.6 increased, from \$5,900 USD in 1990 to \$29,000 USD in 2022. This growth is closely linked to the success of the copper mining sector.

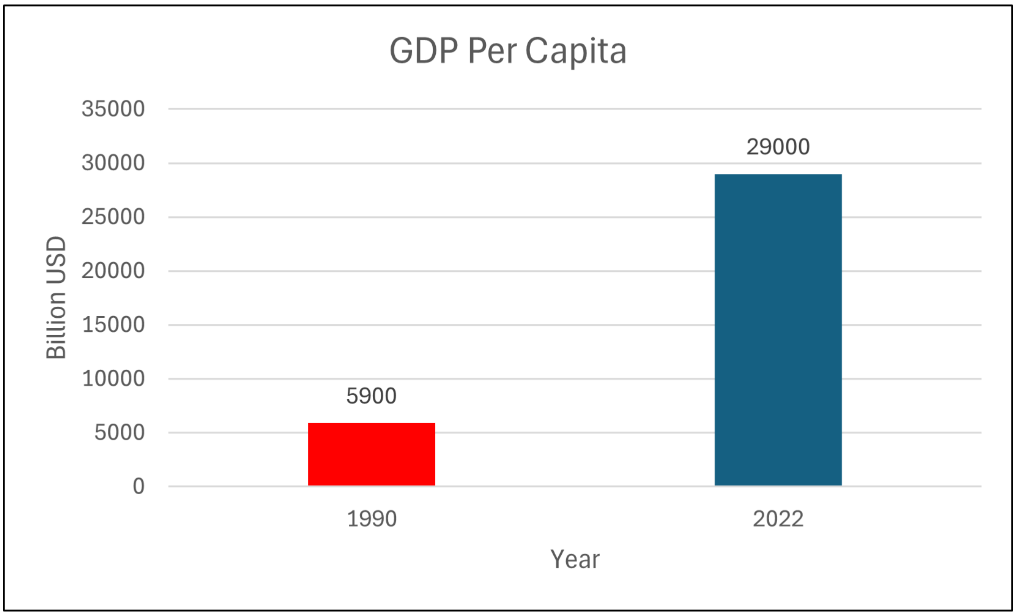


Figure 2.6. Chile's GDP Per Capita Valdivieso [2023]

iv. Chile's poverty levels have dropped significantly, from 68% in 1990 to 10.8% in 2022 as shown in Figure 2.7. This reduction in poverty is largely attributed to the economic opportunities created by copper mining.

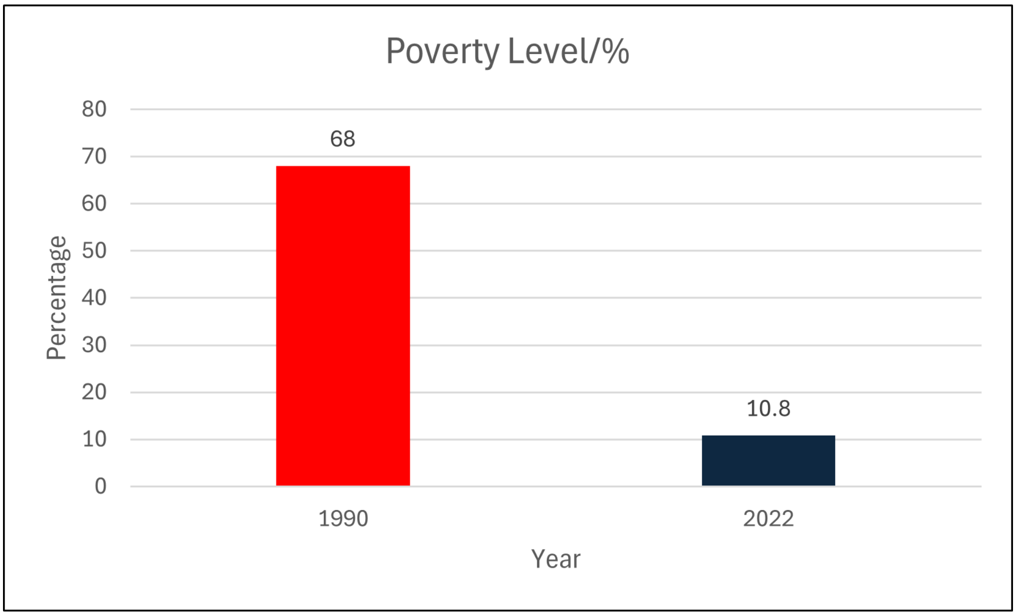


Figure 2.7. Chile Poverty levels in 1990 and 2022Valdivieso [2023]

Forecast for Copper Production

According to projections from Commission [2017a], national copper production is expected to rise by 13.9% by 2028. However, there are risks associated with the depletion of active deposits and a corresponding decline in ore grades. Without significant investments in replacement projects and expansions of existing operations, production could decrease by 31.54% by 2028, reaching just 3.8 million metric tonnes Commission [2017a]. The projected annual decline of 2.87%, shown in Figure 2.8 reflects the challenges facing Chile's copper industry in maintaining current production levels.

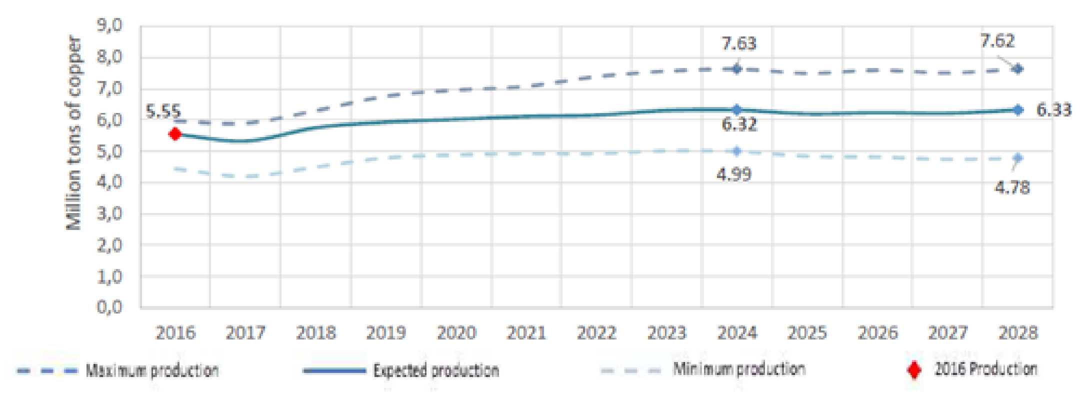


Figure 2.8. Mine copper production 2016 and forecast for 2017–2028 Commission [2017a]

While the forecast suggests continued growth in the short term, the longer-term outlook underscores the need for innovation and investment in new mining technologies and projects to sustain production.

2.2.2 Peru Production

Peru ranks as the world's second-largest copper producer, boasting substantial reserves that remain underexploited. The country is positioned to continue playing a key role in global copper supply, with a robust pipeline of potential investments in new mining projects. Just like Chile, copper is key to Peru's economy, representing 50% of mining exports and 5% of the GDP as of 2017 Bamber et al. [2024]. However, despite its immense copper potential, Peru faces several challenges. Political instability and unfavourable mining policies have hindered the country's ability to maximize foreign direct investment (FDI). This has created uncertainties in the mining sector, slowing down the full exploitation of the country's abundant resources Research [2023].

Exports

Peru's economy is heavily reliant on its mining sector, which accounted for 57% of total exports in 2022 which is approximately 37.62 billion dollars, according to Figure 2.9 from Research [2023]

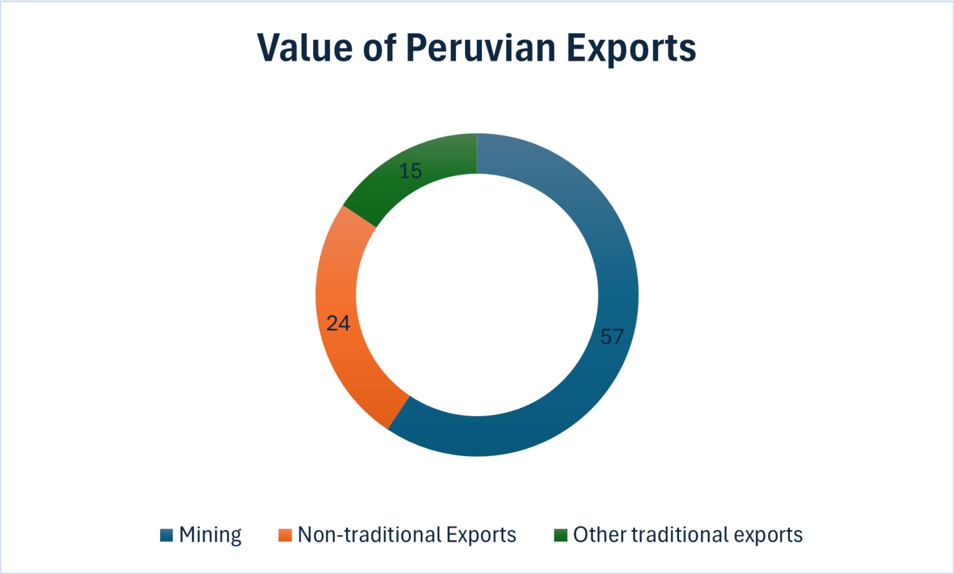


Figure 2.9. Peruvian Exports Value Research [2023]

Of these mining exports shown in Figure 2.10, 52% is directly attributed to copper, underscoring the importance of copper mining to the country's economy.

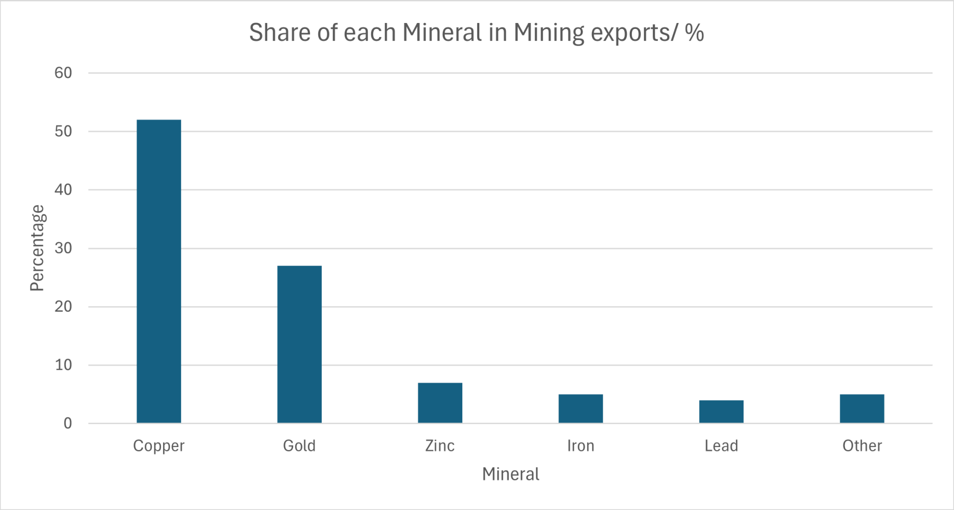


Figure 2.10. Share of each metal in mining exports Research [2023]

This dominance of copper highlights its role as the leading mineral export and a significant driver of Peru's economic activity. Figure 2.10 clearly shows that copper is not only a crucial resource in Peru's mining industry but also the single most dominant export product as of 2022 Research [2023].

Copper Mines

Some of the top-performing copper mines in Peru include Antamina, Cerro Verde, Cuajone, and Toquepala Acosta Ale et al. [2013]. These mines are significant contributors to the country's copper output, with production concentrated in these major operations. Despite this strong base of existing mines, the gap in production between Peru and Chile widened significantly over the years as shown in Figure 2.11.

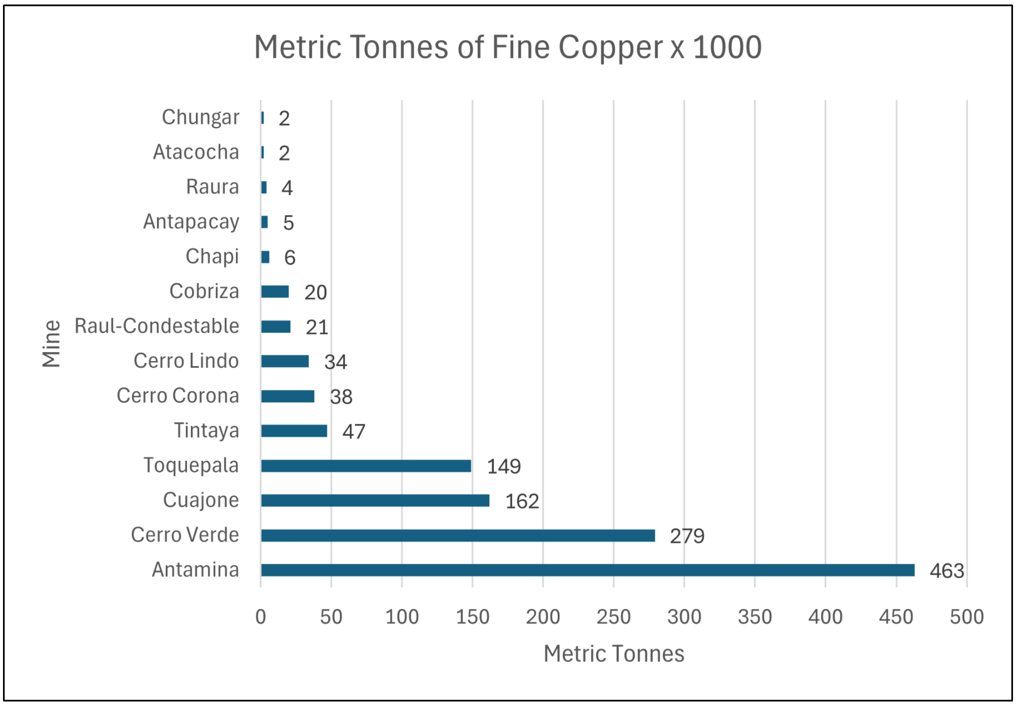


Figure 2.11. Copper Mines Production in Peru (2012) Acosta Ale et al. [2013]

Copper Production Trends: Peru vs. Chile

Historically, Peru and Chile had similar low copper production trends from the 1950s up to the 1970s as shown in Figure 2.12. However, in 1990, a significant divergence occurred, with Chile rapidly outpacing Peru in copper production. Peru's production experienced a significant surge starting in 2015, but it remained second to Chile Acosta Ale et al. [2013]. By 2022, Chile's copper production reached around 8 million metric tonnes, compared to Peru's under 5 million metric tonnes. This production gap can be largely attributed to Chile's more stable mining policies and political environment, which have consistently attracted foreign investments and supported large-scale resource extraction Bamber et al. [2024].

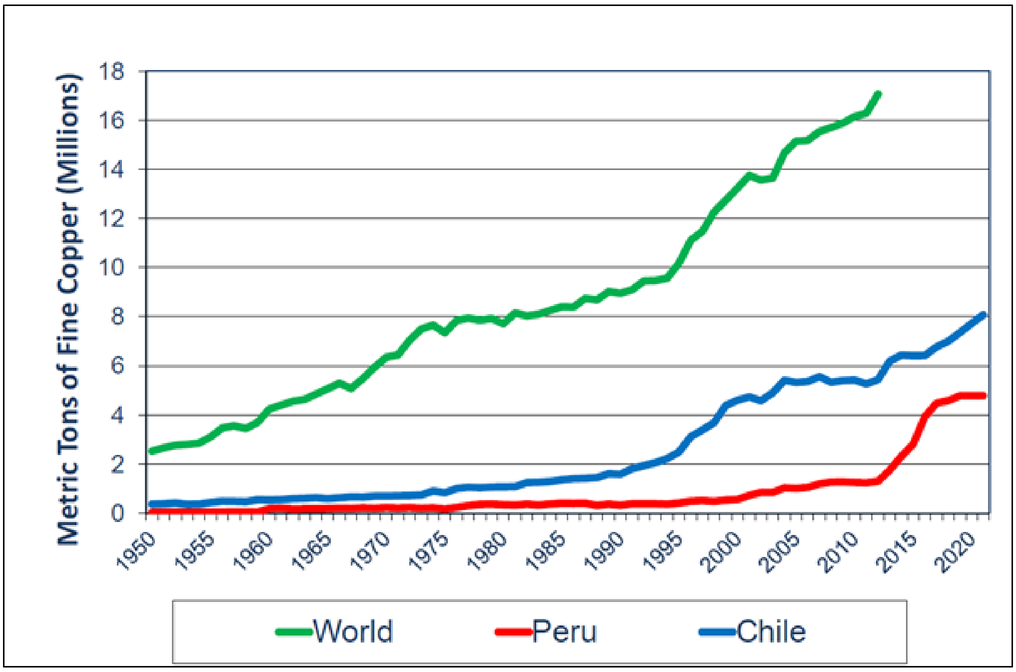


Figure 2.12. Peru and Chile Copper Production to 2021 Acosta Ale et al. [2013]

Challenges in the Copper Sector

Although Peru has experienced significant growth in copper production, there are still areas for improvement, especially in mining policies and political stability. The lack of clear, investor-friendly policies has made it difficult for the country to fully capitalize on its copper reserves. The political unrest of recent years has further complicated efforts to streamline copper extraction and attract new investments into the sector Bamber et al. [2024]. Addressing these governance and policy issues is crucial for Peru to reach its full potential as a global copper leader. By creating a more stable and investment-friendly environment, Peru can attract the foreign capital necessary to boost copper production and close the gap with Chile Bamber et al. [2024].

2.2.3 Democratic Republic of Congo Production

The Democratic Republic of Congo (DRC) is one of the richest countries globally in regarding natural resources, with extensive unexploited reserves of high-grade copper and cobalt. This gives the DRC significant potential in the global mining industry. Despite its minerals wealth, the DRC is classified as a low-income country, suffering from low economic growth, poor human development, and widespread poverty. This is often referred to as the "resource curse", where resource-rich countries experience less development than might be expected due to mismanagement, corruption, and inequality Kalenga [2011].

Copper Consumption and Exports

One reflection of the DRC's underdevelopment is its domestic consumption of copper. The country consumes only 10% of its copper output, with 90% exported. This reliance on exporting raw minerals, rather than processing and utilising them domestically, limits the country's potential for adding value to its resources.

Historical Production Trends

Copper production in the DRC was relatively stable between 1967 and 1990, peaking at close to 500,000 tonnes annually Kalenga [2011]. However, production dropped sharply in the early 1990s due to a combination of factors, including:

i. Regional conflicts and economic wars over natural resources.

ii. Fluctuating mineral prices and global market conditions.

iii. Institutional corruption and plundering of national resources without significant local benefit.

iv. Dependence on foreign investment without developing local capacities or beneficiation processes.

These factors contributed to a sharp decline in production, as illustrated in Figure 2.13.

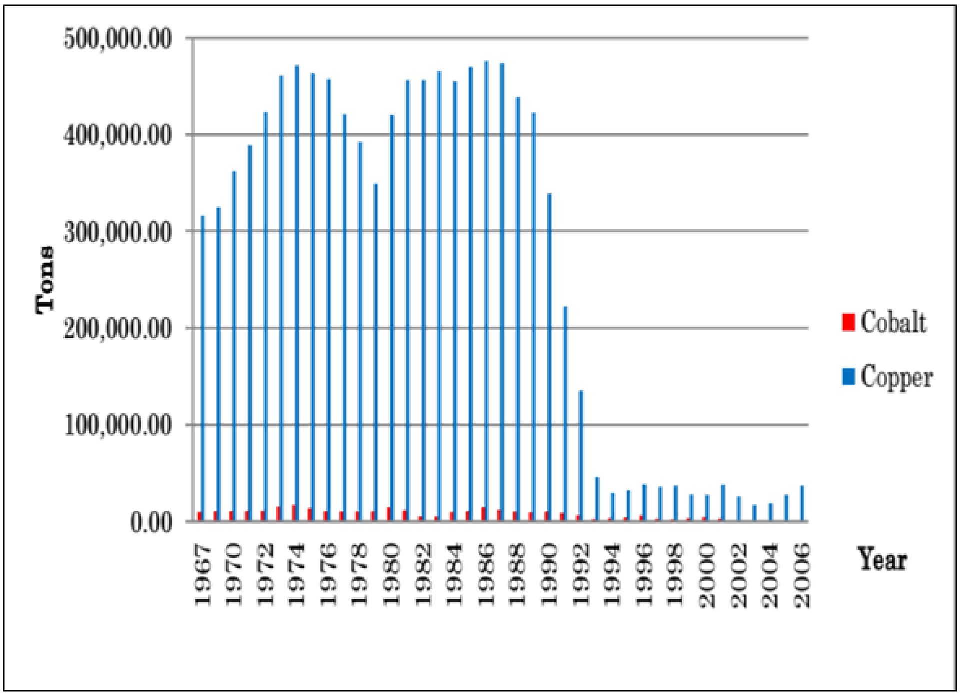


Figure 2.13. Total output of Gecamines Kalenga [2011]

Copper Export Destinations

As a country that exports most of its copper, the DRC's major trading partners are integral to its copper economy. Figure 2.14 shows that China was the leading recipient of DRC's copper, receiving 52% of the total copper exports, followed by Finland (31%) and Zambia (10%) Kalenga [2011]. Other countries that imported were Belgium, Germany, the United Kingdom, and Japan.

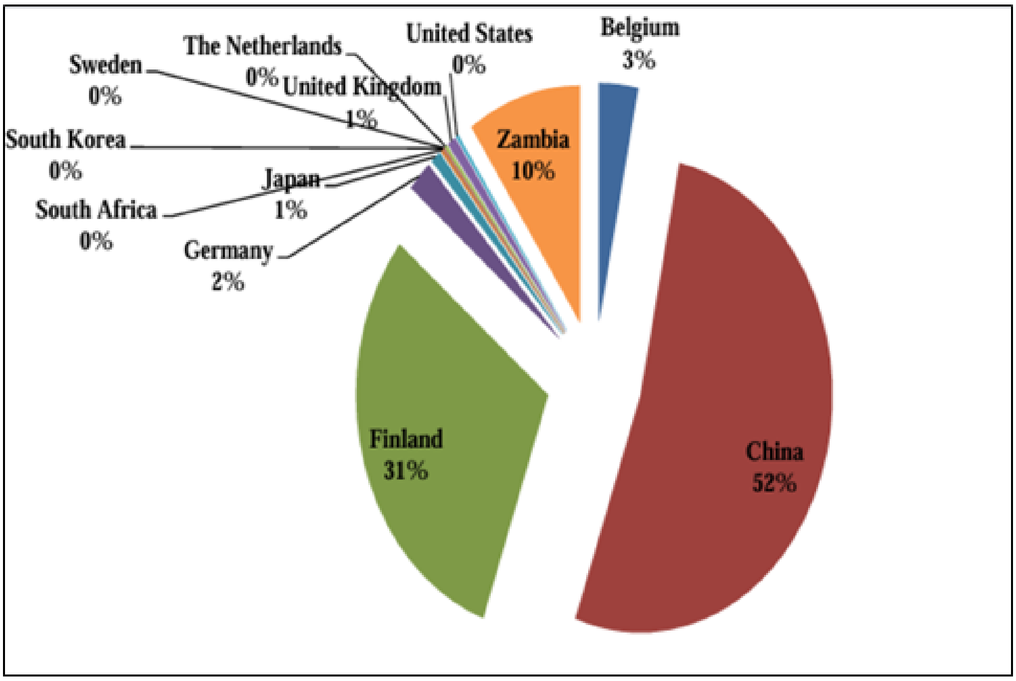


Figure 2.14. Congolese Export of copper and cobalt 2005 Kalenga [2011]

The reliance on exports highlights the DRC's dependency on foreign markets for its copper industry, with limited domestic industrial use or refinement.

DRC's Role as a Critical Copper Producer

Despite its challenges, the DRC has become a critical player in global copper production. In 2017, the DRC accounted for 12% of the world's copper output, and this production as shown in Figure 2.15 increased to 14% by 2021, according to Andreonia and Avenyob [2023] and Musoni et al. [2023]. This steady growth underscores the DRC's importance in meeting global copper demand, particularly as the world shifts towards technologies that require high quantities of copper, such as electric vehicles and renewable energy systems.

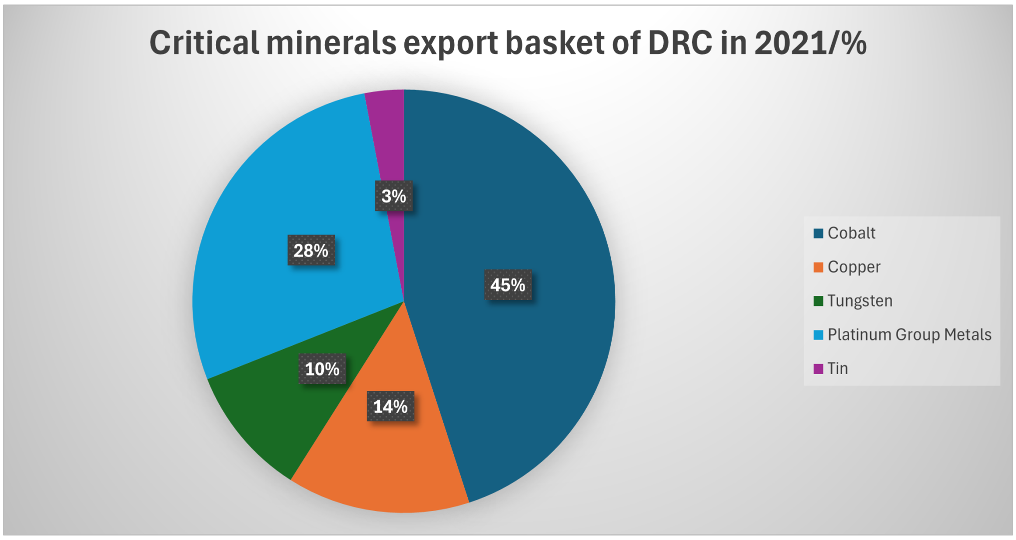


Figure 2.15. Critical minerals export basket of DRC in 2021 Musoni et al. [2023]

The DRC's copper industry continues to grow significantly, with no signs of slowing down. According to reports from Mining [2024] and the Ministry of Mines in the DRC, the country achieved a major milestone in 2023, surpassing Peru to become the world's second–largest copper producer. The DRC produced 2.84 million tonnes of copper, exceeding Peru's production of 2.76 million tonnes during the same period. This significant increase in output highlights the DRC's immense potential and its ability to further cement its position as a global leader in copper production.

Mines and Foreign Investment

The DRC's copper production is dominated by Gecamines, the state-owned mining company, which holds shares ranging from 5% to 40% in various cobalt and copper mines ORE [2021]. Foreign investors, particularly from China, have played a significant role in reviving many of the DRC's previously closed mines. Between 2013 and 2018, Chinese investment peaked, with Chinese firms partnering with Gecamines to develop several large-scale mining operations ORE [2021].

Refinement and Energy Supply

One of the critical challenges facing the DRC's copper industry is its limited capacity for refinement. In 2017, only 76% of the DRC's copper output was refined before export, with much of the copper exported in raw or semi-processed forms, such as black copper. This is mainly due to a lack of reliable energy infrastructure, which limits the country's ability to process its copper. Addressing this energy deficit is crucial for the DRC, to add more value to its copper exports and retain more wealth within the country Andreonia and Avenyob [2023].

2.2.4 China Production

China follows a different path in its copper production process unlike the other top copper-producing countries. While countries like Chile, Peru, and the DRC rely heavily on mining their own copper ores, China has a different strategy due to its limited domestic copper ore resources.

Domestic Resources

As of 2010, primary resources in China contributed only 22.9% of the country's total copper production, according to Global Markets data Figure 2.16. This indicates that China doesn't primarily depend on its ore deposits, unlike copper-rich countries like Chile or the DRC. As a result, China's environmental footprint for copper production is generally lower than the global average, particularly lower than Latin America and Indonesia countries, where vast quantities of material are moved to extract copper Shang et al..

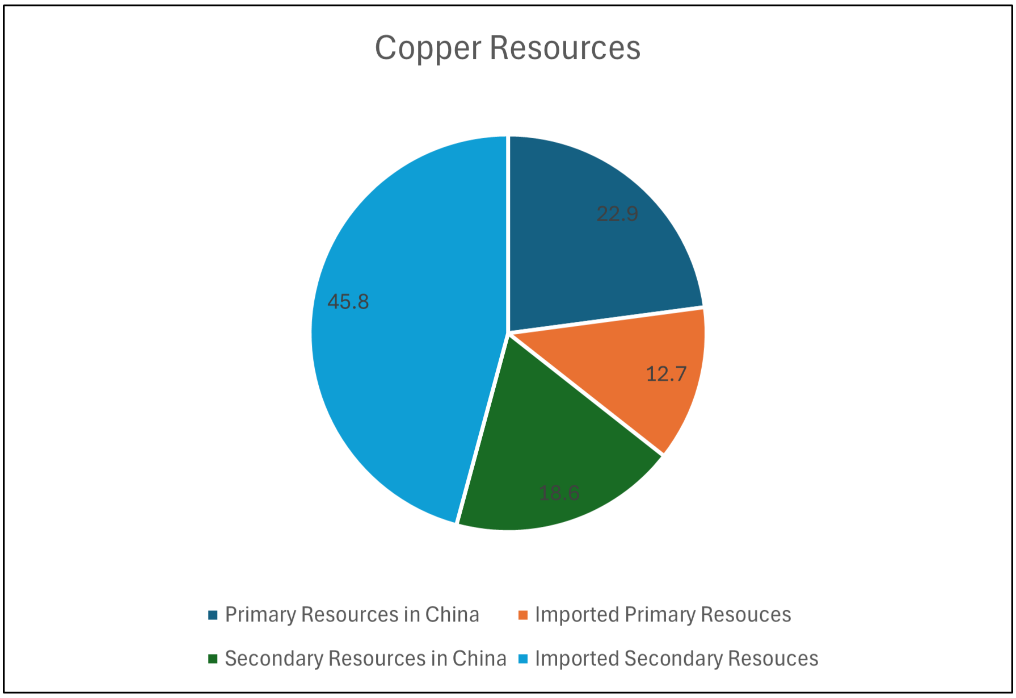


Figure 2.16. China's Copper Resources Shang et al.

Reliance on Imports and Recycling

China has emerged as a copper powerhouse despite its limited supply of domestic copper ores. China's rapid industrialization and economic growth have driven a significant demand for copper, making the country heavily reliant on foreign copper resources to meet its domestic needs. More than 80% of China's total copper consumption during the period from 1950 to 2015 shown in Figure 2.17 below came from imported products. A key measure of this reliance is the Net Import Reliance (NIR), which tracks the percentage of copper demand that is met by imports. Between 1990 and 2015, China's NIR showed a continuous upward trend, reaching its peak in 2013 at 83% Hao et al. [2023]. This reliance reflects the country's insufficient domestic copper supply compared to its growing demand. China imports copper in various forms, with the main imported products being copper concentrate 26%, refined copper 32%, and copper scrap 31%. Copper scrap, plays an important role in the Chinese copper supply chain, with the country importing over 74 million tons of copper waste and scrap from 1990 to 2015. These figures illustrate China's dependence on secondary copper resources to sustain its industrial activities.

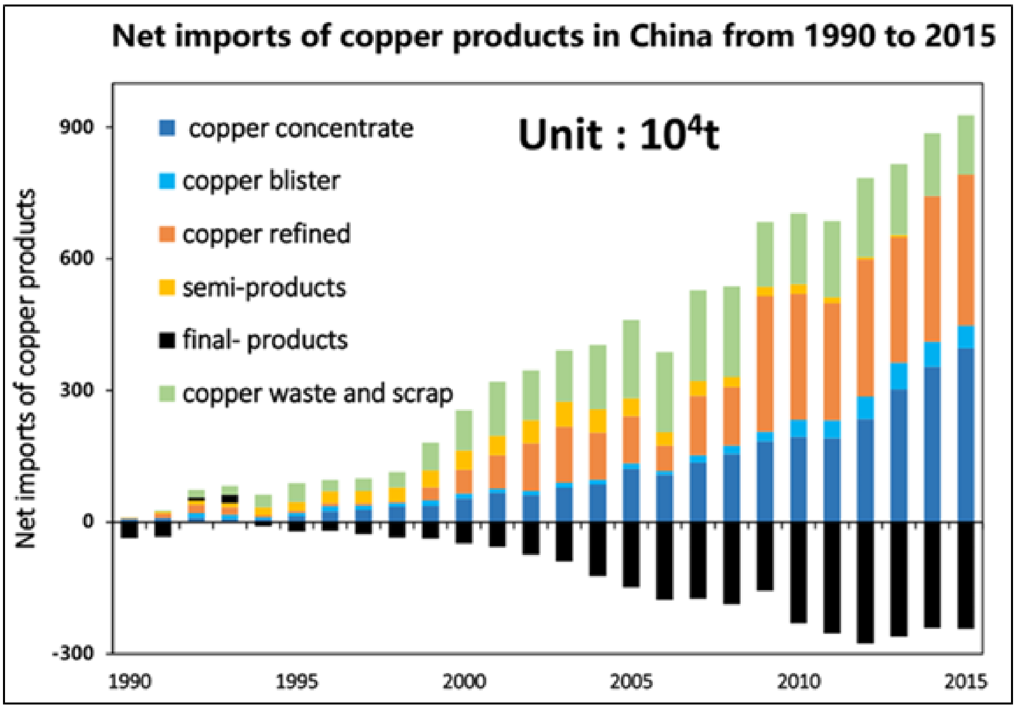


Figure 2.17. China's Net imports of Copper from 1900–2015 Hao et al. [2023]

Global Suppliers of Copper to China

The largest exporters of copper-containing products to China are Chile, Japan, the United States, Australia, and Peru. Chile holds the position of China's largest supplier of copper, exporting over 30 million metric tonnes to China during the period under review Hao et al. [2023]. Other key suppliers are Japan (9.5 MMT), Australia (7 MMT) and Peru (5.9 MMT), which contribute to China's steady inflow of copper resources.

2.2.5 Other Countries

While much attention is given to the top four copper-producing countries, Chile, Peru, China, and the Democratic Republic of Congo (DRC). Other nations are also making significant contributions to global copper production as shown in Figure 2.18. Countries like the United States, Russia, Zambia, Australia, and Mexico are notable for their substantial copper output. These nations are home to some of the world's most efficient and productive copper mines, which are important in meeting the global demand for this essential metal Sprott [2024], for example:

i. The United States has long been a significant player, with large-scale operations such as the Bingham Canyon Mine in Utah, known for its immense size and productivity.

ii. Zambia is part of the Central African Copperbelt, and is renowned for its high-grade deposits and large-scale production, particularly in collaboration with international mining firms.

iii. Australia and Mexico consistently contribute substantial tonnages of copper, with technologically advanced mining operations and robust supply chains.

These countries, alongside the top producers, continue to shape the dynamics of the global copper market as shown by their contribution in Figure 2.18 as of 2022.

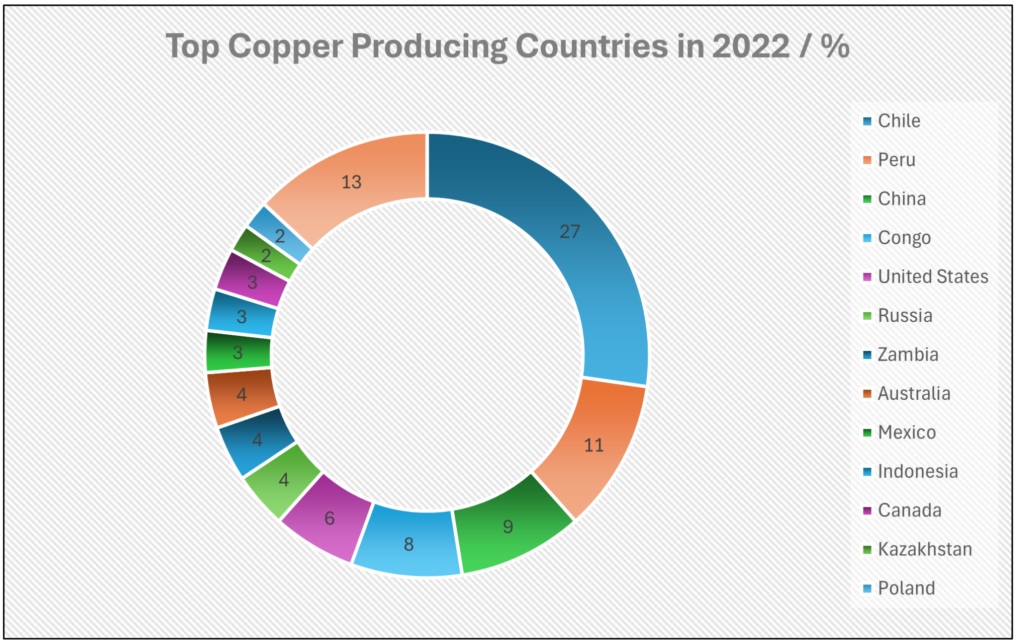


Figure 2.18. Top Copper Producing Countries Sprott [2024]

2.3 Global Market Dynamics of Copper

According to the Supply and Demand Analysis Report, the global refined copper market is valued at over $150 billion annually. In 2013, the US Geological Survey (USGS) estimated that global land-based copper resources amounted to over 3.1 billion tonnes, with 690 million tonnes listed as reserves Wiryono et al. [2023]. Copper production can significantly impact a country's economy. With proper management, it can compensate for the lack of other natural resources, as seen in Chile Wiryono et al. [2023]. The relationship between copper demand and price is crucial; if demand is higher than the recovery rate of secondary resources, the reliance on primary resources grows, placing upward pressure on prices Wiryono et al. [2023].

2.3.1 Global Copper Trade

According to Solutions for Critical Raw Materials for EU Mathieux et al. [2017]. Copper is traded predominantly in three major exchanges:

i. London Metal Exchange (LME), which is traded in 25-tonne lots and quoted in USD per tonne.

ii. Commodity Exchange Division of the New York Mercantile Exchange (COMEX/NYMEX) which is traded in 25,000-pound lots and quoted in US cents per pound.

iii. Shanghai Futures Exchange (SHFE) which is traded in 5-tonne lots and quoted in Renminbi per tonne.

Copper Price Trends and Factors Affecting Prices

Copper's market price is influenced by a various factors, including supply and demand, hedging, stockpiles, GDP, and macroeconomic indicators such as the Consumer Price Index (CPI) and the US Dollar Index (USD Index). Some of them are discussed in detail below:

i. **Macroeconomics**

A country's GDP, commodity prices, and the US Dollar Index are key contributors. For example, when GDP weakens, copper demand tends to decline. For example between 2000 and 2008, the strengthening of China's economy caused a significant rise in copper prices, which later dropped due to the financial crisis. Prices have fluctuated with China being a major influencer due to its consumption of nearly half of the world's copper production Mathieux et al. [2017].

ii. **Microeconomics**

These include supply, demand, stockpiles, and hedging. Stockpiles can ease short-term pressure on prices and help stabilise them during supply interruptions Wiryono et al. [2023]. The US Dollar Index also plays a major role; when the USD strengthens, copper prices tend to fall, and when the dollar weakens, prices rise. Hedging: Hedging provides price stability for buyers and sellers, ensuring a consistent price for a set quantity of copper even if market conditions fluctuate Wiryono et al. [2023].

Between 2000 and 2008, the price of copper tripled, reaching $6,963 USD/tonne before a significant drop at the end of 2008 as shown in Figure 2.19 coinciding with the global financial crisis Mathieux et al. [2017].

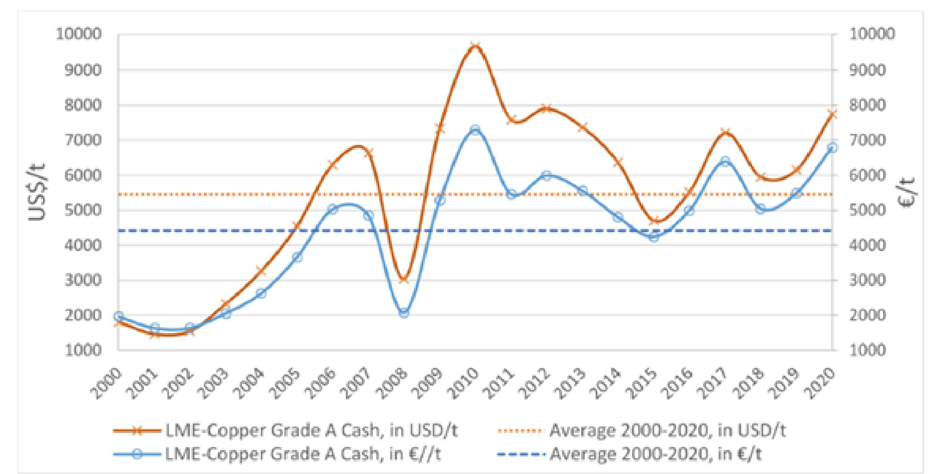


Figure 2.19. Annual average price of copper between 2000 and 2020 Mathieux et al. [2017]

Demand for Copper in Renewable Energy

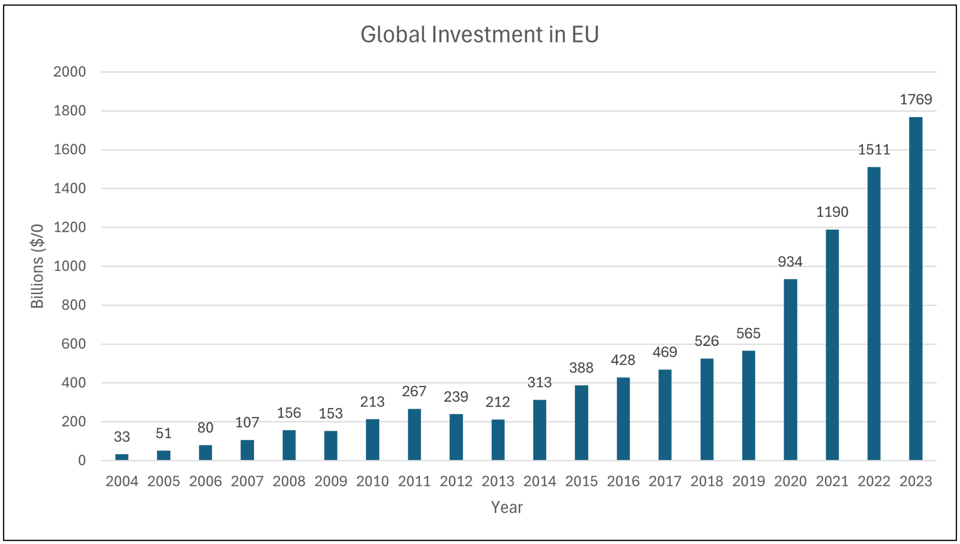


Figure 2.20. Global Investment in Clean Energy Sprott [2024]

As global electricity consumption is projected to increase by 85% by 2050, copper demand is expected to surge Sprott [2024]. Copper is crucial for developing clean energy technologies such as electric vehicles (EVs), solar panels, wind power, and hydroelectric power. Investment in clean energy reached $1.8 trillion in recent years as shown in Figure 2.20. This, coupled with rising copper prices, could drive the development of new copper mining projects.

Copper's role in renewable energy underscores its strategic importance in global sustainability efforts. Despite predictions of a global long-term supply deficit, global mined copper production is expected to grow by 4.1%, reaching 23.5 million metric tonnes, with contributions from Chile, DRC, and Russia Sprott [2024].

Copper Inventory and Investment Risks

According to recent reports from Sprott [2024], copper exchange inventories are at historic lows, covering just three days of global demand. This creates a risk of sudden price spikes if buyers make large drawdowns to secure supplies. Investment in new copper mines is likely to increase to mitigate these risks and meet growing demand. Higher prices may be necessary to incentivise the development of additional production capacity.

2.3.2 Importance of Copper in the European Union (EU)

Copper Production and in the EU

Import Reliance

The EU is heavily reliant on copper imports. Table 2.1 illustrates the EU's dependence on extracted and processed copper from 2016 to 2020.

	Copper (Extraction)	Copper (Procession)
Global Production/ metric tonnes	20 538 727.00	24 132 631.00
EU Consumption/ metric tonnes	2 054 007.30	3 688 055.50
Import Reliance(%)	48	17

Table 2.1. EU Copper Consumption 2016-2020 Mathieux et al. [2017]

Copper Concentrates

According to Solutions for Critical Raw Materials Journal Mathieux et al. [2017] the EU imports 48% of its extracted copper, with major suppliers from the period under review being Poland, Chile, Brazil and Peru and the other countries and their respective percentages shown in Table 2.2.

EU Copper Supplier Countries	Percentage by supply of copper
Poland	20
Chile	15
Brazil	10
Peru	10
Spain	9
Bulgaria	5
Sweden	5
Canada	4
Portugal	3
Georgia	3
US	3
Other	13

Table 2.2. EU Copper supply (Extracted) in, 2016-2020 Mathieux et al. [2017]

The EU has a lower import reliance on processed copper, with key suppliers being Germany, Poland, and Spain, the other countries and their respective percentages are shown in Table 2.3

EU Copper Supplier Countries	Percentage by supply of copper
Germany	18
Poland	15
Spain	11
Belgium	10
Russia	8
China	7
Sweden	6
Bulgaria	6
Finland	4
Austria	3
Congo	3
Other	9

Table 2.3. EU Copper supply (Processed) in, 2016-2020 Mathieux et al. [2017]

The EU's dependence on imported copper has increased over the past two decades, with imports rising from 630,000 tonnes in 2000 to 1.2 million tonnes in 2017-2018 as shown in Figure 2.21. According to Solutions for Critical Raw Materials journal Mathieux et al. [2017] Chile was the primary supplier during this period, followed by Peru, Indonesia, Brazil, and Argentina. EU exports of copper ores and concentrates also increased from 66,164 tonnes in 2000 to 280,000 tonnes in 2020 as shown in Figure 2.21.

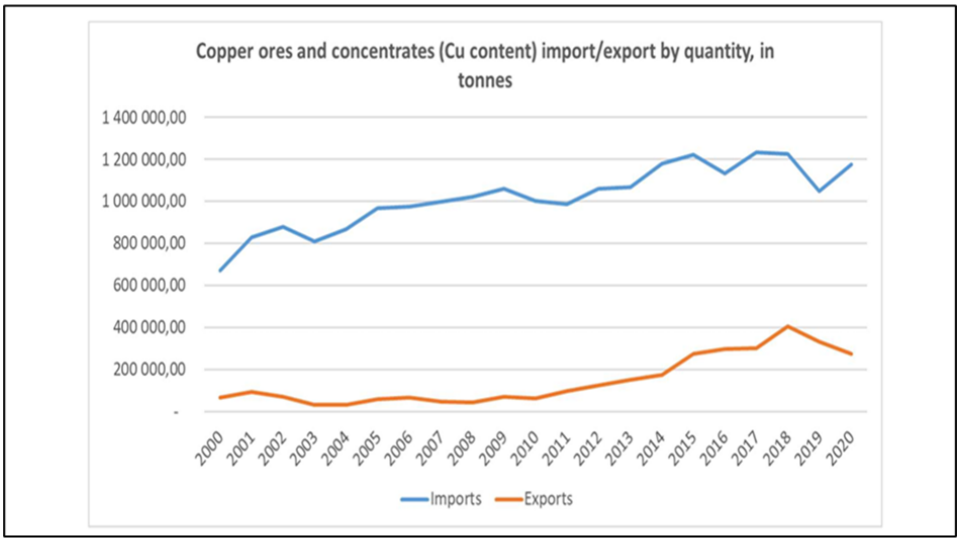


Figure 2.21. EU trade flows of Copper containing Copper ores and concentrates (Cu content, CN 26030000) from 2000 to 2020 (Eurostat, 2022) Mathieux et al. [2017]

Refined Copper

The main import partners for refined copper are Chile (47%), Russia (24%), and Peru (5%). A notable trend has been the rising import of refined copper from the Republic of Congo, which saw an increase from 40 tonnes in 2004 to 118,000 tonnes in 2013, growing 17 times between 2011 and 2013 as shown in Figure 2.22 from Mathieux et al. [2017].

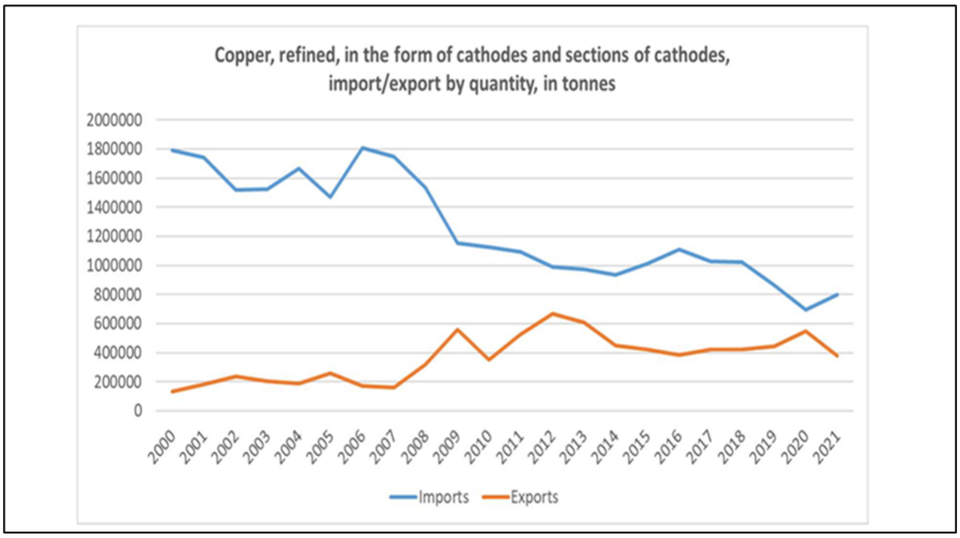


Figure 2.22. EU Trade flows of Refined copper (CN 74031100) from 2000 to 2020 Mathieux et al. [2017]

Contribution to the European Green Transition

Copper is a critical raw material for the EU's green transition, as it is essential for the development of electricity networks, electric vehicles, and renewable energy technologies like solar and wind power Sprott [2024]. Given the anticipated surge in demand for these technologies, copper will continue to play a strategic role in achieving the Sustainable Development Goals (SDGs) and driving the circular economy within the EU as shown in Figure 2.23

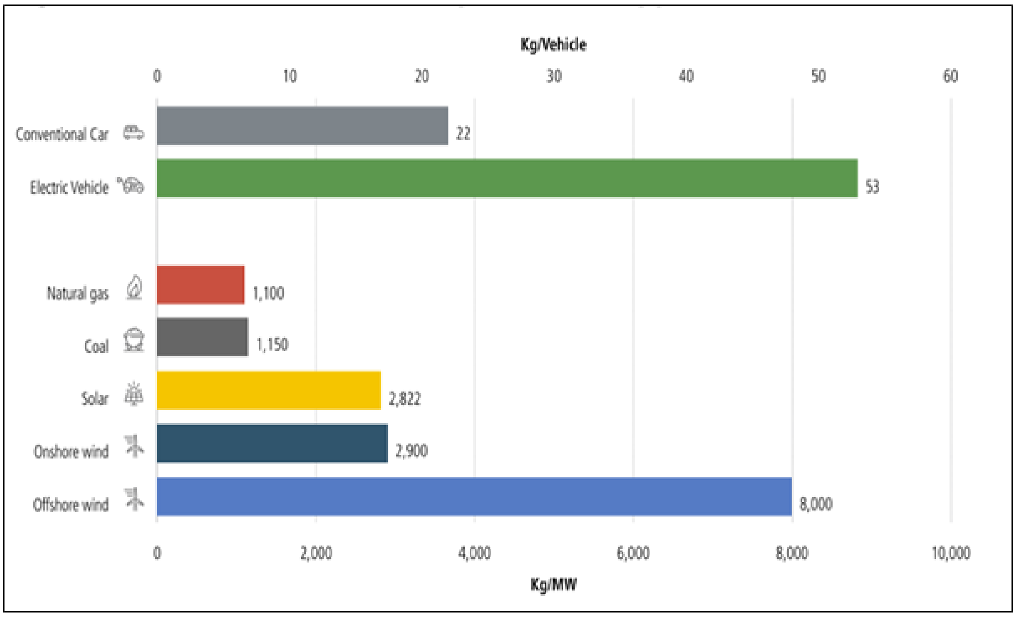


Figure 2.23. EVs and Renewables Copper Requirements Sprott [2024]

2.4 Sustainable Development Goals (SDGs)

The Sustainable Development Goals (SDGs) represent a global agenda aimed at equitable, socially inclusive, and environmentally sustainable economic development. The mining industry, including copper mining, holds a significant potential to mobilize substantial resources, human, technological, and financial toward advancing these goals. While mining can create jobs, improve innovation, and foster infrastructure development, it also presents challenges such as environmental degradation, displacement of populations, and increased conflict when poorly managed. Given its global reach and resource-intensive nature, copper mining plays a crucial role in achieving the SDGs.

2.4.1 Sustainable Mining Practices

Efforts are underway to improve transparency and sustainability in the copper mining sector. For example, the Rocky Mountain Institute, in collaboration with institutions such as the MIT Centre for Transportation & Logistics and the Columbia Centre for

Sustainable Investment, has launched initiatives to standardize carbon accounting frameworks for the minerals industry. These frameworks will enable more accurate emissions calculations and help drive the decarbonization of mining.

Mining's Direct Contributions to the SDGs

According to Atlas [2016] the scope of mining activities presents opportunities for the sector to contribute directly to several SDGs:

i. **SDG 1 – End Poverty**

   Mining generates substantial revenues through taxes, royalties, and dividends, which can be reinvested in economic and social development.

ii. **SDG 6 – Clean Water and Sanitation & SDG 15 – Life on Land**

   Mining impacts landscapes and water systems, necessitating responsible land and water management.

iii. **SDG 7 – Affordable and Clean Energy & SDG 13 – Climate Action**

   Mining is energy and emissions-intensive, making efforts to transition to cleaner energy sources and reduce carbon footprints vital.

iv. **SDG 8 – Decent Work and Economic Growth**

   Mining provides jobs and training but can also contribute to economic differences if not managed equitably.

v. **SDG 9 – Industry, Innovation, and Infrastructure**

   Mining fosters economic development by stimulating innovation and infrastructure development.

vi. **SDG 16 – Peace, Justice, and Strong Institutions**

   Responsible mining can promote peaceful societies by respecting human rights and avoiding conflicts with local communities Atlas [2016].

2.4.2 Copper's Role in Sustainable Development

Due to its unique properties, copper is key in many areas of sustainable development due to its unique properties. Its applications in energy access, and sustainable technologies further solidify copper's centrality to global development efforts. Copper is also highly recyclable, maintaining its properties without degradation, making it critical to the circular economy and life-cycle analyses of end-use products Association [2017].

The International Copper Association (ICA)

The International Copper Association (ICA) plays a crucial role in aligning copper mining with global sustainability goals. With 39 members representing most of the global copper production, the ICA drives initiatives that promote sustainable development. Each year, the association's members invest $50 million in programs that aim to enhance copper's contribution to sustainability, focusing on responsible production, environmental stewardship, and social responsibility Association [2017].

The International Copper Association Australia (ICAA)

The International Copper Association Australia (ICAA) goes a step further by emphasizing the need for copper mining and processing to align with energy transitions and industrial decarbonization. The ICAA advocates for increased transparency across the copper supply chain, responding to growing consumer and investor demand for more sustainable and circular business practices Sykes et al. [2020]. This aligns with global trends toward green procurement and sustainable sourcing.

2.5 Mine Tailings

2.5.1 Generation

Mine tailings are the waste materials that remain after the extraction of the economically valuable fraction from mineral ores. They typically consist of a slurry made up of finely ground rock, water, and chemical reagents used in the ore processing. The composition of tailings varies depending on the mineralogy of the ore deposit and the methods employed in processing Baker et al. [2020]. Figure 2.24 shows that in 2016, an estimated 8.85 billion tonnes of mine waste was generated globally, with approximately 46% of this attributed to copper tailings Baker et al. [2020]. This large percentage is a direct result of the growing demand for copper, driven by population growth, declining ore grades, and the shift toward renewable energy. As ore grades continue to decline, more material must be processed to extract the same amount of metal, leading to increased waste generation Baker et al. [2020]

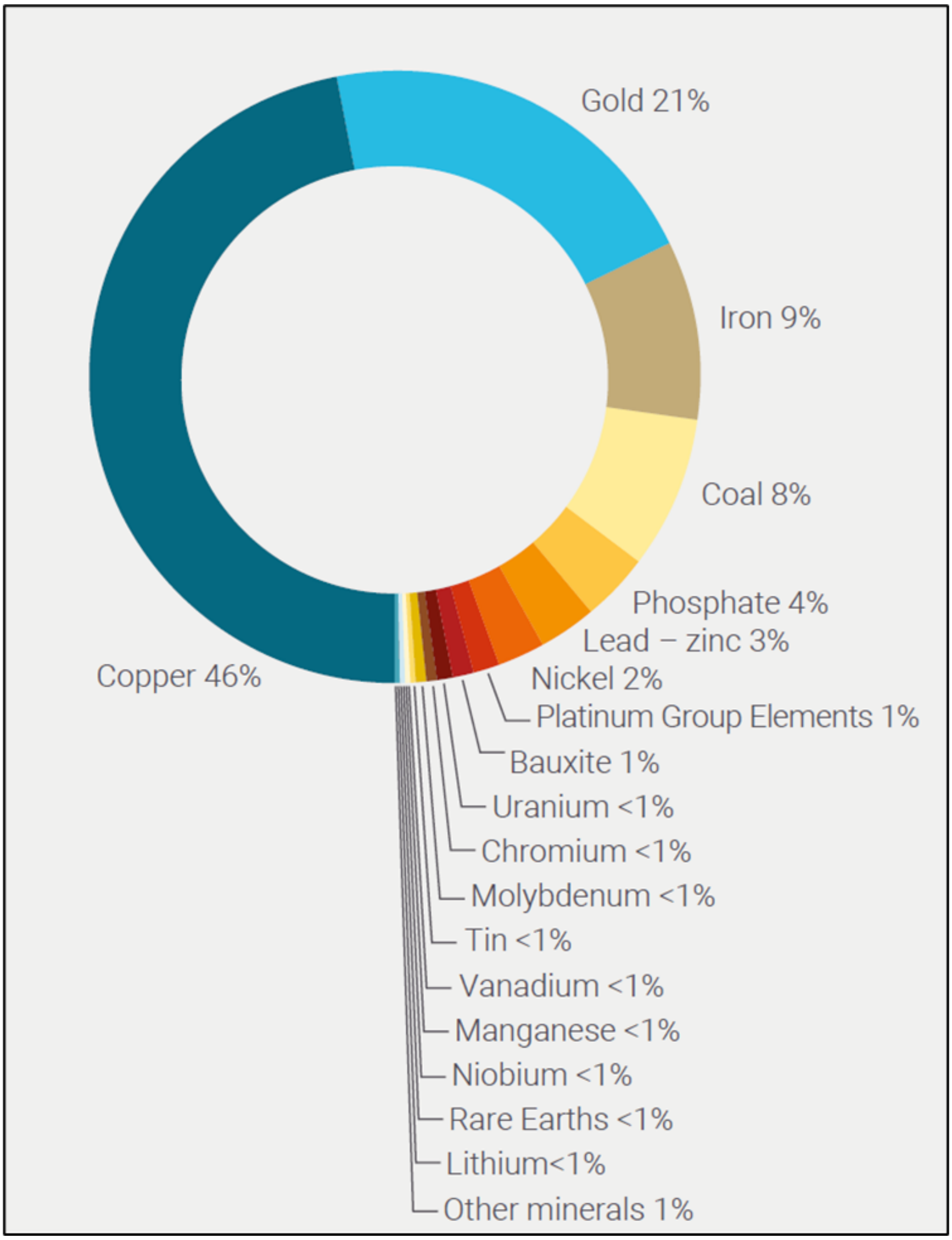


Figure 2.24. Percentage of global tailings volume per commodity in 2016 Baker et al. [2020]

2.5.2 Composition

Sulfide tailings are often associated with heavy minerals due to the nature of their occurrence. These tailings typically contain various heavy metals such as copper, lead (Pb), zinc (Zn), iron (Fe), arsenic (As), aluminium (Al), and silicon (Si) Chen et al. [2014].

Research involving X-ray fluorescence (XRF) has confirmed the presence of these metals in tailings samples. According to KARA [2021] the most abundant inert chemical composition is SiO_2. Good recoveries are generally achieved in industrial flotation circuits for particles in the $30 - 50\,\mu$m size range, while particles outside this range are often lost in the process and rejected to tailings streams due to physical constraints during the pulp and froth phases of conventional flotation equipment Mankosa et al. [2016]. This suggests that copper tailings could still possess favourable grades, particularly since copper ore grades are in decline today.

2.5.3 Storage Facilities

Tailings are generally stored on-site in well-designed facilities, with conventional methods relying on raised embankments, often referred to as tailings dams. These storage structures are designed to contain tailings and prevent their release into the environment. Tailings embankments are constructed using one of three main methods. These are upstream, downstream, or centreline, with each technique determining the direction of embankment growth in relation to the initial dyke at the base as shown in Figure 2.25 from Baker et al. [2020]

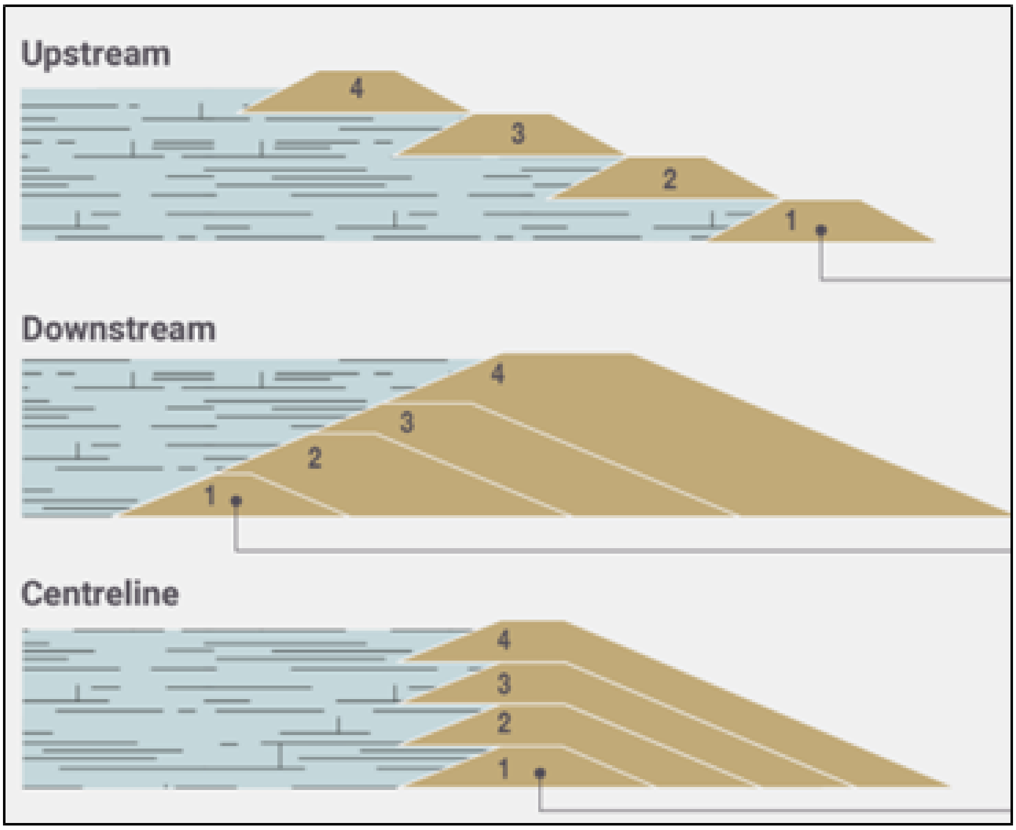


Figure 2.25. Common methods of tailings embankment construction Baker et al. [2020]

i. **Upstream Method**

In this design, the embankment grows in the direction of the tailings, meaning the crest moves upstream. This method offers reduced initial investment costs compared to the downstream method (EMSWGG course Riggio [2024]).

ii. **Downstream Method**

Considered the most stable design, the embankment grows in the opposite direction of the tailings, with the crest moving downstream. The method is recognized as the most structurally stable and resilient to potential failures, though it is also more costly and requires more materials Baker et al. [2020]

iii. **Centreline Method**

In this approach, the embankment grows vertically along the centreline of the original dyke. It is a moderation between the upstream and downstream methods.

Tailings dams must be designed to withstand the loading conditions expected during the mine's life, including during post-closure when the mine is no longer operational. Failures of tailings dams have historically resulted in catastrophic consequences, including loss of life, environmental devastation, and significant economic costs associated with containment and remediation efforts Riggio [2024]. In addition to storage in dams, tailings can also be used as backfilling material in previously mined-out underground areas or open pits. This method can reduce the environmental footprint of surface tailings storage and improve the stability of underground workings.

2.6 Environmental Effects of Tailings

Copper tailings, particularly those associated with sulfidic deposits, pose long-term environmental risks due to their potential for acid mine drainage (AMD) and the release of heavy metals into the environment. According to the German Environment Agency, approximately 85% of copper ores mined globally are sulfidic ores, with chalcopyrite being the primary mineral. This type of ore increases the likelihood of acid mine drainage, which can lead to significant environmental harm near mining sites. Furthermore, certain copper deposits, especially in countries like China, the USA, and the Democratic Republic of Congo (DRC), are associated with low-level exposure to radioactive elements, adding further environmental concerns Atibu et al. [2022].

2.6.1 Acid Mine Drainage (AMD)

Acid mine drainage refers to the outflow of acidic water from mining sites, primarily caused by the oxidation of iron sulphide minerals, such as pyrite, that are often associated with copper, gold, lead, and silver ores. When these sulphide minerals are exposed to air and water (rainfall) during mining activities, they undergo oxidation, leading to the production of sulfuric acid. This acid not only lowers the pH of nearby water bodies but also accelerates the leaching of heavy metals like lead and arsenic, contaminating soil and water ecosystems Riggio [2024].

Process

The process of acid mine drainage (AMD) can be understood through the following reactions:

Oxidation of Pyrite

$$2\,\mathrm{FeS_2(s)} + 2\,\mathrm{H_2O} + 7\,\mathrm{O_2} \longrightarrow 2\,\mathrm{Fe^{2+}} + 4\,\mathrm{(SO_4)^{2-}} + 4\,\mathrm{H^+}$$

In this step, pyrite reacts with water and oxygen, leading to the formation of ferrous ions ($\mathrm{Fe^{2+}}$), sulphate ions (${\mathrm{SO_4}}^{2-}$),and hydrogen ions ($\mathrm{H^+}$) which contribute to the acidity of the water Riggio [2024].

Further Oxidation of Ferrous Ions

$$4\,\mathrm{Fe^{2+}} + \mathrm{O_2} + 4\,\mathrm{H^+} \longrightarrow 4\,\mathrm{Fe^{3+}} + 2\,\mathrm{H_2O}$$

In this reaction, ferrous ions are oxidized to ferric ions ($\mathrm{Fe^{3+}}$), particularly in acidic environments with a pH between 3.5 and 4.5. This reaction is often catalysed by bacteria such as Metallogenium Riggio [2024].

Pyrite Dissolution by Ferric Ions

$$\mathrm{FeS_2(s)} + 14\,\mathrm{Fe^{3+}} + 8\,\mathrm{H_2O} \longrightarrow 15\,\mathrm{Fe^{2+}} + 2\,\mathrm{(SO_4)^{2-}} + 16\,\mathrm{H^+}$$

The ferric ions can dissolve more pyrite, creating a cyclical process that continuously generates more acid. The dissolution of pyrite by ferric iron produces ferrous ions and sulfate, contributing to further acid generation Riggio [2024].

Precipitation of Ferric Hydroxide

$$\mathrm{Fe^{3+}} + 3\,\mathrm{H_2O} \longrightarrow \mathrm{Fe(OH)_3(s)} + 3\,\mathrm{H^+}$$

Ferric ions precipitate as ferric hydroxide, which is often visible as a yellow, orange, or red deposit on streambeds. This precipitate can suppress aquatic habitats and disrupt ecosystems Riggio [2024].

Impact of Sulfuric Acid and Heavy Metals

Sulfuric acid generated by AMD is highly corrosive and toxic to most living organisms. The increased acidity of water bodies makes them inhospitable to aquatic life, disrupting ecosystems and reducing biodiversity Coil et al. [2014]. Additionally, acidic water leaches heavy metals such as lead, arsenic, and cadmium from surrounding rocks into the environment. The accumulation of these toxic metals poses severe risks to aquatic ecosystems and eventually human health Riggio [2024].

Role of Mining on AMD

Mining activities accelerate the formation of AMD and heavy metal contamination by exposing large surface areas of sulphide-bearing rocks which were initially buried to oxidation. The generation of mine tailings significantly increases the exposed surface area, leading to faster acid generation and more widespread environmental impacts compared to natural processes Riggio [2024].

2.7 Valorisation of Copper Tailings

In a global environment where copper demand is rising and copper prices are steadily increasing, reprocessing copper tailings has become a more logical and economically viable decision. In many tailings' deposits from the last century, copper content remains sufficiently high to justify economic exploitation. Advancements in extraction technologies now allow the recovery of copper that was previously discarded as tailings due to inefficiencies in older copper extraction processes. High copper prices also contribute to the growing interest in tailings reprocessing, as tailings historically considered waste have now become potential valuable resources. For example, some tailings from the last century contained up to 0.75% copper, which may be higher than the current deposits being mined, which typically range from 0.2% to 0.8% copper. However, each tailings deposit is unique, requiring customised reprocessing procedures. The economic feasibility of reprocessing tailings can also be improved if environmental rehabilitation is prioritized by governments or communities, allocating funds to restore areas degraded by tailings. After removing toxic heavy metals, the remaining material could potentially be sold for construction use. Since the material in tailings dams has already undergone mining and some initial processing, such as crushing and grinding, the costs of reprocessing are often lower than those associated with traditional mining.

2.7.1 Recovery of Residual Metal

Reprocessing plants for copper tailings are already operational in several parts of the world, with more expected to come online. In Chile, a reprocessing plant extracts copper from tailings with copper grades ranging from 0.12% to 0.27%. XRF analysis of tailings samples indicates that copper content varies between oxidized and unoxidized samples, with the latter showing higher copper content, averaging 0.16%. This suggests that unoxidized tailings may be more promising for reprocessing than their oxidized counterparts. Different chemical processes can be applied to extract metals from ore or tailings, including pyrometallurgy, hydrometallurgy (solvent-based), and electrometallurgy (high electrical power). The most common method is pyrometallurgy, specifically smelting, which is energy-intensive but efficient in extracting metals once copper ores have been concentrated through mineral processing. Physical separation methods also play an essential role in minimizing energy consumption compared to chemical processes.

2.7.2 Cement Production

Studies have explored the potential of utilizing copper tailings in cement production, but definitive results are still limited. After removing heavy metals, tailings may serve as a raw material for cement or construction products. Tailings used as a replacement for cement in mixtures can influence the final product's properties, although the variability in tailings composition from different sources makes general assumptions difficult, KARA [2021]. Onuaguluchi and Eren [2012]found that using pre-dried copper tailings as an additive in cement increased water demand and negatively affected consistency. However, this drawback was minimised, when pre-wetted tailings were used, and compressive strength improved. Another study by Sigvardsen et al. [2018] examined the use of copper tailings as a partial replacement for fine aggregates in cement mixtures. Results indicated that up to 60% of fine aggregates could be replaced with copper tailings, yielding mixtures with good strength and durability characteristics.

2.8 Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodological approach used to evaluate a product's environmental impacts throughout its entire life cycle, from the extraction of raw materials to material processing, manufacturing, distribution, use, maintenance, and end-of-life disposal or recycling. This approach helps quantify the environmental consequences associated with each stage of the product's life. According to the Society of Environmental Toxicology and Chemistry (SETAC, 1993), LCA provides a comprehensive framework for understanding and mitigating the environmental impacts of industrial and natural systems Universita degli Studi di Firenze [2024].

2.8.1 Fields of Application

LCA has become widely used across various sectors, from industrial production units to natural systems. It supports a range of stakeholders, including manufacturers, service providers, consumers, and policymakers Universita degli Studi di Firenze [2024]. Its applications include:

i. Informing policymakers in creating environmentally sustainable development policies and strategies.

ii. In the private sector, LCA helps companies comply with environmental laws, standards, and certifications.

iii. LCA is integral to eco-labelling and product environmental certification processes, which assess the life cycle impacts of products and processes.

iv. Businesses utilize LCA to optimize production processes, reduce waste, and minimize environmental footprints.

2.8.2 European Approaches to LCA

In Europe, the Environmental Management and Audit Scheme (EMAS) explicitly references LCA as a key criterion for sustainability. The ISO 14000 family of standards defines the application of LCA as a tool for assessing environmental issues. Specifically, ISO 14040 (aligned with guidelines proposed by SETAC) Universita degli Studi di Firenze [2024] outlines four main steps for conducting an LCA:

Goal and Scope Definition

The goal of an LCA study is to define the reasons for conducting the assessment and specifies the intended audience, whether technical, political, or social. The scope defines the functional aspects of the product or process under evaluation, determining the system boundaries and specifying the assumptions and limitations of the study.

Inventory Analysis

The inventory analysis involves quantifying the system's inputs such as raw materials and energy and outputs, like emissions and waste of the system throughout its life cycle. This phase reconstructs the flow of energy and materials from raw material extraction to the final product, forming a model of the real system Universita degli Studi di Firenze [2024]. The data collected during the inventory analysis is grouped into six categories:

i. Raw materials

ii. Fuels or energy sources used throughout the process.

iii. Energy content of feedstock required in various stages.

iv. Solid waste generated during production.

v. Emissions to air, including greenhouse gases.

vi. Emissions to water.

Impact Assessment

The impact assessment phase aims to evaluate the environmental modifications caused by emissions and resource consumption identified in the inventory analysis. This step translates data into environmental impacts, classified into several broad categories such as Universita degli Studi di Firenze [2024]:

i. Ecological Impacts on biodiversity and ecosystems.

ii. Health Impacts due to exposure to harmful substances.

iii. Resource Depletion, of natural resources like energy, minerals, and water.

iv. Social Impacts, on human activities and social infrastructure.

The impact assessment process is divided into three steps Universita degli Studi di Firenze [2024]:

i. Choosing relevant environmental impact categories based on the study goals such as Eco-Indicator 99 or ReCiPe).

ii. Assigning each emission or resource use to its corresponding impact category.

iii. Quantifying the contribution of each substance or activity to the impact categories by applying specific characterization factors such as Global Warming Potential for CO_2 emissions).

Interpretation

Interpretation is the final phase of the LCA, in which the inventory analysis and impact assessment results are analysed to draw meaningful conclusions. This phase includes Universita degli Studi di Firenze [2024]:

i. Highlighting the most important environmental impacts based on the results of the LCA.

ii. Assessing the completeness of the data, the outcomes' sensitivity, and the findings's consistency.

iii. Based on the assessments, conclusions are drawn about the environmental impacts. Recommendations are made to improve environmental performance.

2.8.3 Previous Work on LCA of Tailings Reprocessing

Several studies have explored the environmental and sustainability aspects of tailings reprocessing through Life Cycle Assessment (LCA) methodologies. These studies have focused on evaluating the environmental trade-offs, benefits, and limitations of recovering valuable secondary materials from mine tailings, with specific attention to tailings from copper and other sulphidic mining operations. Two prominent studies by Di Maria et al. [2024] and Adrianto et al. [2023]) provide insights into the technical and environmental challenges, and the opportunities, associated with tailings valorisation.

Resources, Conservation & Recycling Journal

Goal

Di Maria et al. [2024] aimed to evaluate the sustainability hotspots of the NEMO technologies, which were designed for the treatment and valorisation of mining residual tailings, specifically sulfidic mine residues. The goal was to recover secondary metals and inerts as secondary construction materials. His work also aimed to assess the social, economic, and environmental impacts of tailings reprocessing through a Life Cycle Sustainability Assessment (LCSA) framework.

Methodology

The framework incorporated three separate analyses, which are Environmental Life Cycle Assessment (E-LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA). These assessments were conducted independently but used the same initial assumptions, including system boundaries and functional units. The methodology was aligned with the UNEP guidelines for LCSA (2012) and the ISO 14040 framework, covering goal definition, inventory analysis, impact assessment, and interpretation phases Di Maria et al. [2024].

Results

The study revealed a mixed environmental impact. There was a 22% increase in climate change impacts due to reprocessing, but a significant 98% reduction in the use of mineral resources compared to primary mining Di Maria et al. [2024]. Economic analysis indicated positive outcomes, with a net present value (NPV) ranging from 8.2 million Euros to 48 million Euros, depending on the purity of recovered cobalt. Social analysis highlighted key risks such as fair worker compensation and limited access to local resources.

Recommendations

Di Maria et al. [2024] recommended further exploration of strategies to enhance the environmental performance of tailings valorisation processes, with particular attention to minimizing the climate change impacts and improving the overall sustainability of reprocessing technologies. He also called for improved data quality and modelling approaches for S-LCA, especially in lower-income regions where local data may be lacking.

Science of the Total Environment Journal

Goal

Adrianto et al. [2023] focused on evaluating the environmental benefits and trade-offs of copper tailings reprocessing in the EU, particularly emphasising secondary resource recovery and its potential to replace primary materials. The study also sought to project large-scale impacts by 2050 and assess the implications of tailings-derived products on the environment and market.

Methodology

Adrianto et al. [2023] developed a systematic framework that included goal and scope definition, scenario development, modelling, data collection, and environmental impact assessment. The study applied a "zero-burden assumption," excluding tailings generation's environmental burdens. Several scenarios were developed to simulate the environmental implications of reprocessing sulfidic copper tailings, focusing on secondary metals and construction materials like cement and ceramics.

Results

The study demonstrated that reprocessing copper tailings could produce secondary materials, but market constraints limited the penetration of tailings-based products. For example, secondary cement products were projected to replace less than 5% of the market share by 2050 Adrianto et al. [2023]. Additionally Adrianto et al. [2023] identified challenges related to the availability of raw materials necessary for secondary product manufacturing. Environmental analysis revealed trade-offs between climate change impacts and ecotoxicity, with greenhouse gas emissions increasing slightly under specific reprocessing scenarios.

Recommendations

Adrianto et al. [2023] recommended extending the scope of LCA studies to cover the use phase and end-of-life impacts of tailings-derived products. He also emphasized the need for further research into advanced metallurgical processes that could improve the recoverability of critical elements lost in tailings. Regulatory challenges were also noted as barriers to scaling up tailings reprocessing technologies, and Adrianto et al. [2023] stressed the importance of navigating national approval processes to ensure market entry for new products.

Chapter 3

Technical Evaluation of Valorisation Methods for Copper Tailings

3.1 Introduction

This chapter outlines the methodology employed to investigate the technical approaches used to recover residual copper and other valuable minerals from sulfidic tailings, along with tailings reduction techniques. While mine tailings were historically considered waste, advancements in technology now allow for the recovery of residual metals that may still be present in significant quantities. Additionally, valorising mine tailings helps minimize the environmental risks associated with their disposal. This chapter examines flotation and leaching methods for their technical feasibility in recovering minerals. Furthermore, techniques that repurpose tailings into usable products are assessed, helping to reduce waste volume and contribute to sustainable mining practices.

3.2 Methodology

The focus is on two main aspects; residual mineral recovery and tailings reduction. The focus will be on evaluating the efficiency of residual mineral recovery techniques, the effectiveness of tailings reduction processes, and the technical feasibility of scaling these methods for broader industrial use. A comparative analysis will be done at the end to identify the most promising approaches. Each case study will include:

i. Source and characterization of the tailings.

ii. Methodology employed for mineral recovery or tailings reduction.

iii. Key results, such as recovery rates, produced construction material properties.

3.2.1 Residual Mineral Recovery Techniques

This section evaluates flotation and leaching methods for copper recovery, focusing on their efficiency and technical feasibility in extracting valuable residual metals from mine tailings. The evaluation process includes:

i. **Flotation Techniques**

   Flotation is assessed for separating copper and other valuable metals from tailings. Through case studies, the effectiveness of different flotation reagents is examined, focusing on copper grade and recovery percentages.

ii. **Leaching Techniques**

   Acid leaching methods are explored for their potential to dissolve and extract copper from sulfidic tailings. The impact of acid concentrations and leaching times is investigated in the case studies.

iii. **Comparison of Techniques**

   The flotation and leaching case studies are compared based on their efficiency, recovery rates, and scalability. The objective is to determine which method is more suitable for various types of copper tailings based on their mineral composition.

3.2.2 Tailings Reduction Techniques

In addition to recovering residual minerals, reducing tailings volume is critical for minimizing environmental impact and optimizing resource use. The case studies explored various methods for transforming tailings into usable materials. These include:

i. **Geopolymers**

   In some case studies sulfidic tailings were incorporated as fine aggregates in the production of geopolymer and cement materials. The potential of mine tailings to improve mechanical properties and reduce cement consumption was evaluated.

ii. **Ceramic and Construction Applications**

   Tailings were also tested as raw materials in ceramic formulations, specifically in producing roof tiles and bricks. Mechanical properties such as compressive and flexural strength were assessed at different firing temperatures.

iii. Comparison of Techniques

The geopolymers, roof tiles and brick case studies are compared based on their compressive strength, leaching rates and water absorption. This comparison aims to identify which method offers the most effective solution for producing a viable substitute product from tailings.

3.3 Results and Analysis of Residual Mineral Recovery Techniques

3.3.1 Case A: Recovery of Residual Copper using Floatation

Source and Characterization of the tailings

Brest et al. [2021] focused on a tailings sample from the southern region of the Democratic Republic of Congo (DRC). The tailings consisted of sulphide and oxide complexes, with chalcopyrite as the primary copper mineral. Heterogenite and hematite were the main cobalt and iron-bearing minerals, respectively. The chemical composition of the sample, determined through Atomic Absorption Spectroscopy (AAS), is presented in Table 3.1:

Element	Copper	Cobalt	Iron	Calcium	Sulphur
Grade (wt%)	1.6	0.6	3.09	1.45	12.03

Table 3.1. Chemical composition of mine tailings Brest et al. [2021]

The high sulphur content of 12.03wt% (weight percent) indicates a significant presence of sulphide minerals, mostly chalcopyrite. This composition has the potential for copper and cobalt recovery and the potential to cause acid mine drainage due to the presence of heavy metal in significant concentrations. The particle size distribution analysis revealed a D90 = 75 μm, indicating fine particles, suitable as flotation feed material.

Methodology

Flotation experiments were conducted using a 2.5 L Denver flotation cell to improve copper recoveries from the tailings. A slurry was prepared by mixing a specific mass of tailings with water to achieve pulp densities between 1.15 and 1.25 g/cm^3 Brest et al. [2021]. The experiments involved conditioning the pulp with reagents such as Sodium Isobutyl Xanthate as the collector, Sodium Silicate as the dispersant, and Hydro froth as the frother. Flotation was carried out at neutral pH 7, with agitation at 325 rpm and an airflow of 7 L/min Brest et al. [2021]. Table 3.2 presents the flotation parameters tested:

Condition	–1	0	1
Pulp density	1.15	1.2	1.25
Collector SIBX (g/t)	10	55	100
Frother G41 (g/t)	10	45	80
Sodium Silicate (g/t)	50	100	150

Table 3.2. Flotation Parameters Brest et al. [2021]

Results and Analysis

The flotation parameters' effects on total copper recovery and process efficiency are summarized in Table 3.3.

	Total copper Recovery (%)	Efficiency (%)
Pulp density	–0.09	–0.25
Collector	+1.66	–5.31
Frother	+0.0038	–0.25
Dispersant	–0.01437	+0.92
Average	7.05	73.7

Table 3.3. Effects of the parameters Brest et al. [2021]

i. Pulp Density

Increasing pulp density negatively affected copper grade -0.09% as shown in Figure 3.1 and flotation efficiency -0.25% in Table 3.3. This might be caused by increased in slurry viscosity, which hinders particle flotation.

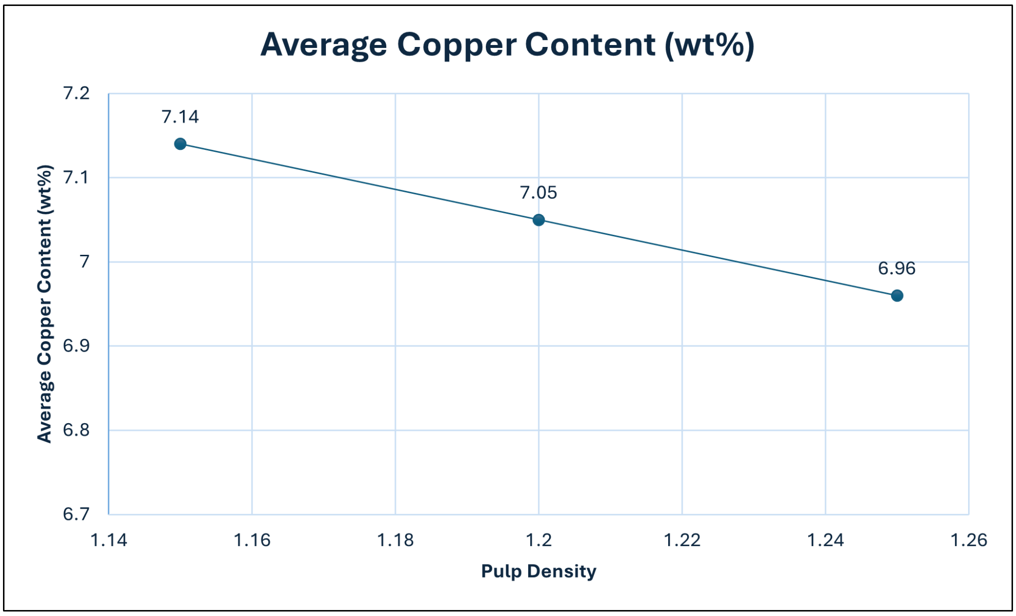


Figure 3.1. Pulp Density Brest et al. [2021]

ii. Collector Dosage

Increasing the collector dosage had the most significant impact on copper recovery, wimproving it by +1.66% in Figure 3.2. However, excessive collector dosage reduced the process efficiency by -5.31%. This might be due to froth instability or over-collection of gangue material.

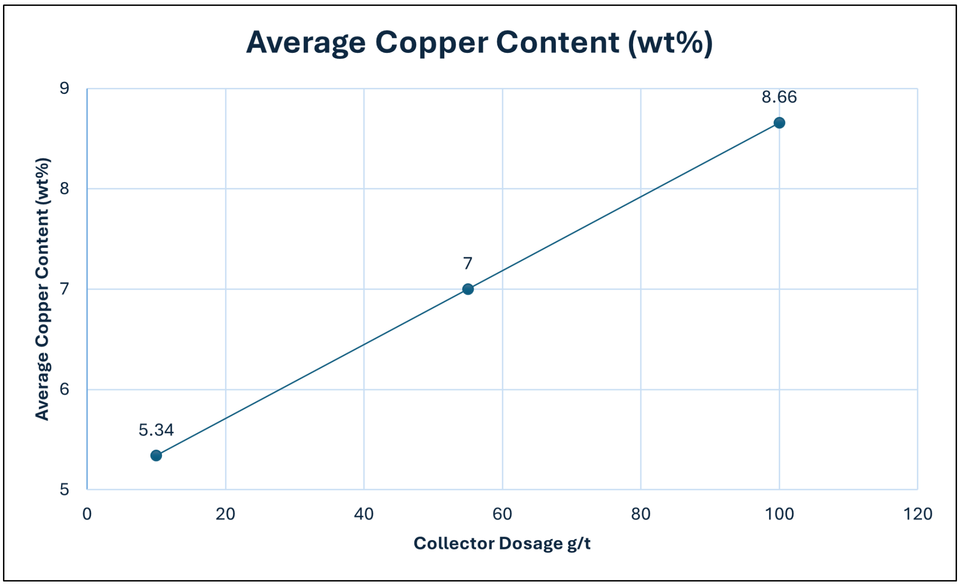


Figure 3.2. Collector Dosage (g/t) Brest et al. [2021]

iii. **Frother**

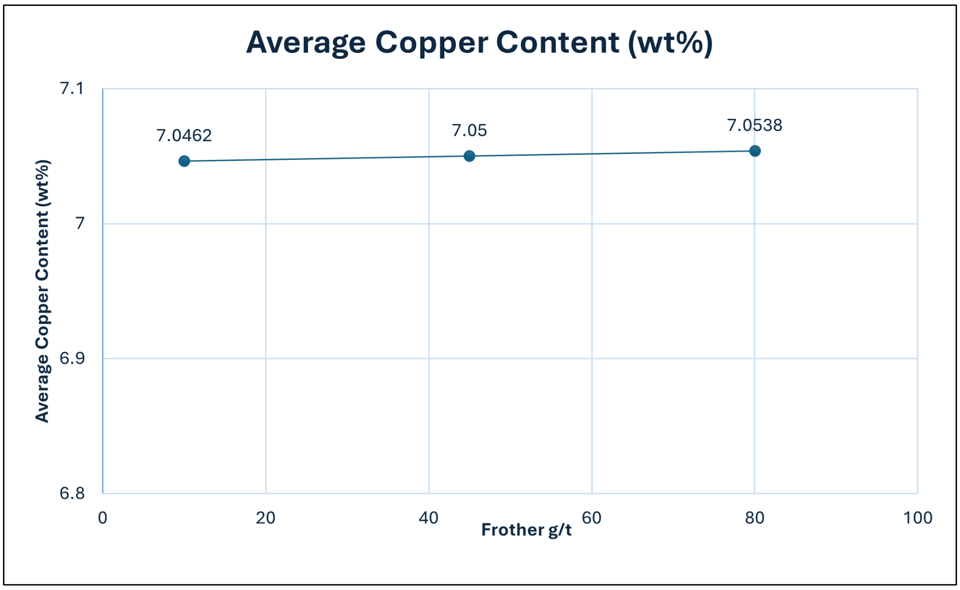


Figure 3.3. Frother (g/t) Brest et al. [2021]

Frother had relatively minor effects on copper recovery and efficiency. A higher frother dosage had a negligible impact on copper grade (+0.0038%) in Figure 3.4 but slightly decreased efficiency -0.25%.

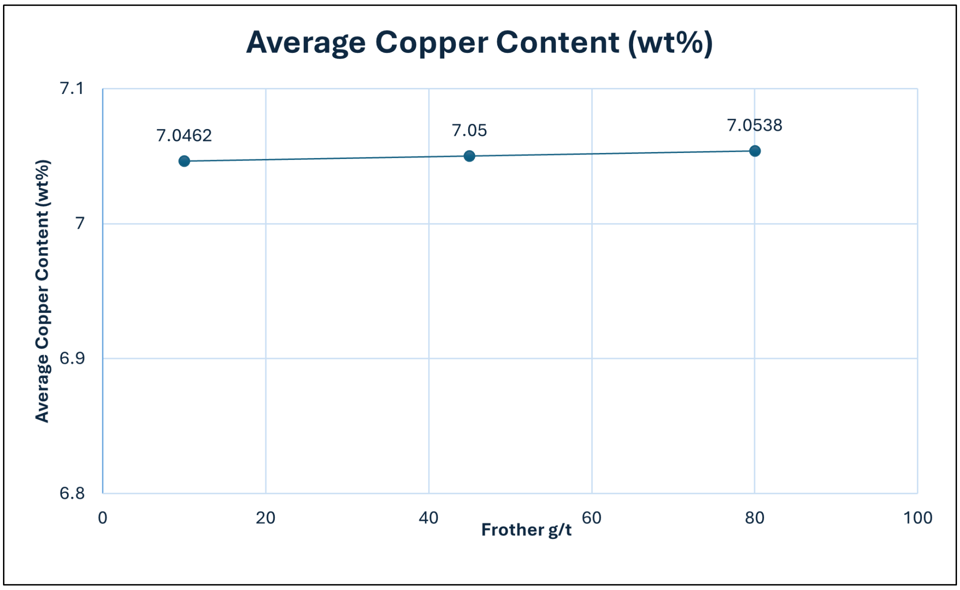


Figure 3.4. Frother (g/t) Brest et al. [2021]

iv. **Dispersant**

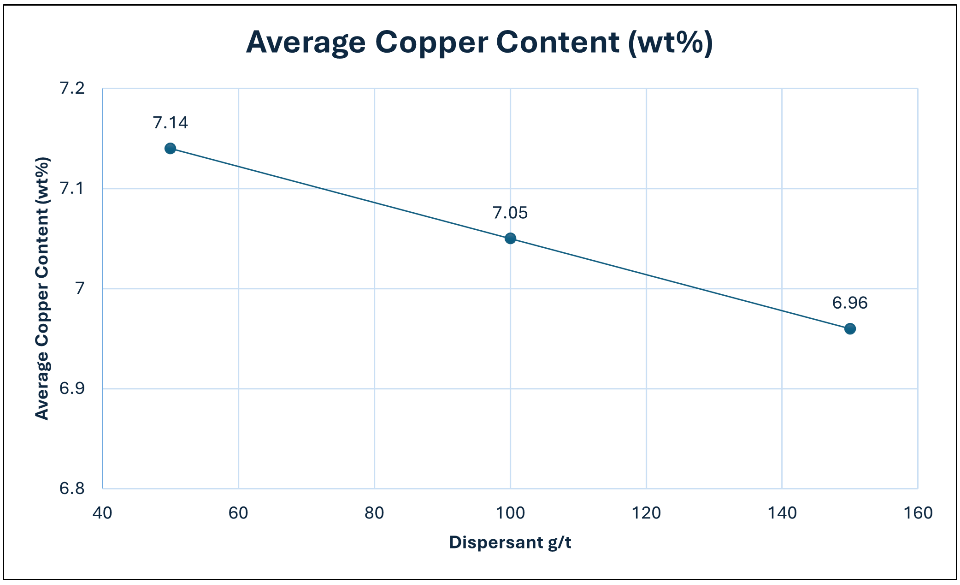


Figure 3.5. Dispersant Brest et al. [2021]

Dispersant dosage also had a minor effect on copper recovery and efficiency. When reduced, this results in improved flotation efficiency +0.92% but slightly reduced copper grade -0.014% as shown in Figure 3.5.

v. **Average Grade**

The average copper grade of 7.05% and flotation efficiency of 73.7% demonstrate the high feasibility of flotation recovery for copper from these tailings.

Conclusion for Case A

The results indicate that collector dosage is the most critical parameter in improving copper recovery during flotation. While pulp density and dispersant are less critical, they should be optimized to maintain process efficiency. The study suggests that collector dosage should be carefully controlled to balance copper grade improvement without compromising efficiency Brest et al. [2021]. Based on these findings, recommendations can be made to optimize flotation conditions for larger scale copper recovery from tailings, with an emphasis on maintaining process stability and minimizing environmental impacts.

3.3.2 Case B: Recovery of Residual Copper using Floatation and magnetic separation

Source and Characterization of the tailings

This case study focuses on a copper tailing site, in Taltal, Chile. These tailings are historically significant and come from porphyry copper deposits in Chile, a region known for its extensive repository of tailings data Drobe et al. [2021]. The tailings are primarily composed of magnetite, which is about 20% by weight, with a copper content of 0.56%, which is higher than the typical historical copper grades found in tailings from the 1930s which averaged 0.33% Drobe et al. [2021].

Tailing Composition

A detailed mineralogical analysis using XRD was performed to identify the trace minerals in the homogenized sample, a mix of fine and coarse-grained materials. The mineralogical composition is presented in Table 3.4.

Mineral	Concentration (%)
Pyrite	1.0
Apatite	0.5
Atacamite	0.4
Halite	0.4
Ankerite	0.4
Chalcopyrite	0.2

Table 3.4. Tailings Mineralogical Composition Drobe et al. [2021]

Atacamite, is a secondary copper chloride mineral indicates the presence of residual copper in the tailings with a significant percentage of 0.4%. The concentration of chalcopyrite was found to be insignificant at 0.2%. The average copper grade of 0.56% and the magnetite content of 20% make these tailings a potential candidate for the recovery of copper and iron Drobe et al. [2021].

Methodology

Two different separation schemes were tested to recover copper and iron from the Taltal tailings. The two approaches were:

i. **Flotation Followed by Magnetic Separation (F-M)**

In this scheme, flotation was first used to recover copper, and the flotation tailings were subjected to magnetic separation to recover iron. The flotation process involved multiple steps, including reagent addition and pH control to optimize the recovery of copper. The flotation process lasted 3 minutes and was repeated 3 to 5 times to maximize copper pre-concentrate quality Drobe et al. [2021]. After flotation, magnetic separation was performed to remove magnetic impurities mainly magnetite from the copper pre-concentration.

ii. **Magnetic Separation Followed by Flotation (M-F)**

In the M-F sequence, the tailings were first subjected to magnetic separation to remove magnetite before flotation to recover the remaining non-magnetic copper concentrate. The tests conducted in this second scheme, are based on the optimum flotation conditions identified in the first series of tests done. The idea was to reduce the interference of magnetic particles in the flotation process, thereby improving the copper recovery efficiency Drobe et al. [2021].

Results and Analysis

The results for the two separation sequences are presented in Table 3.5

Separation sequence	Flotation – Magnetic separation	Magnetic – Flotation separation
Copper Recovery%	45.9–66.2	44.2
Grade %	1.2–2.2	2.04
Fe recovery %	64	74
Fe content %	60	59.8

Table 3.5. Mineral Recovery Sequence Drobe et al. [2021]

i. Copper Recovery

F-M Sequence: Copper recovery in this sequence ranged between 45.9% and 66.2%, with an average recovery of 56% as shown in Figure 3.6. This higher recovery rate indicates that flotation followed by magnetic separation is more effective in copper recovery.

M-F Sequence: Copper recovery in the MF sequence was lower at 44.2%, indicating that starting with magnetic separation results in reduced copper recovery, likely due to losses of fine copper particles during magnetic separation.

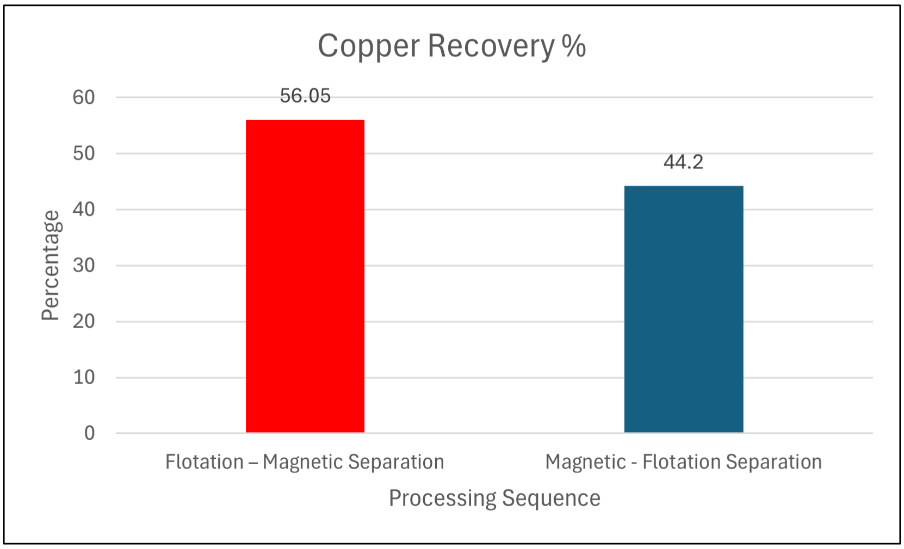


Figure 3.6. Copper Recovery Drobe et al. [2021]

ii. Copper Grades

F-M Sequence: The copper grade in the FM sequence ranged from 1.2% to 2.2%. Figure 3.7 presents the average grade of 1.7

M-F Sequence: The copper grade in this sequence was slightly higher at 2.04%. This indicates that while copper recovery is lower in the M-F sequence, the resulting copper concentrate is of higher grade, which may have economic advantages in some scenarios

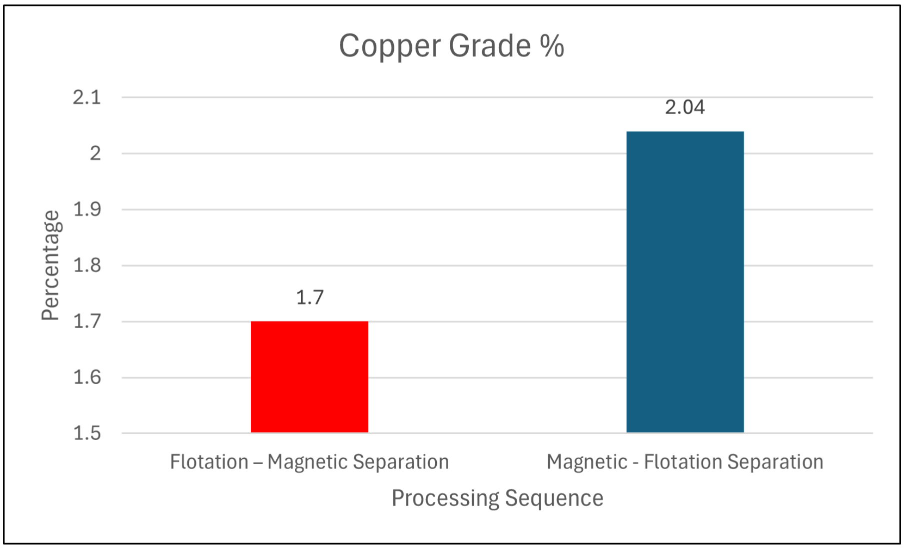


Figure 3.7. Copper Grade Drobe et al. [2021]

iii. **Iron Recovery**

F-M Sequence: Iron recovery in this sequence was 64%, slightly lower than that of the MF sequence.
M-F Sequence: The iron recovery was 74% in Figure 3.8, indicating that the M-F sequence is more effective for recovering iron. The removal of magnetic minerals at the start of the process enhances the efficiency of iron recovery.

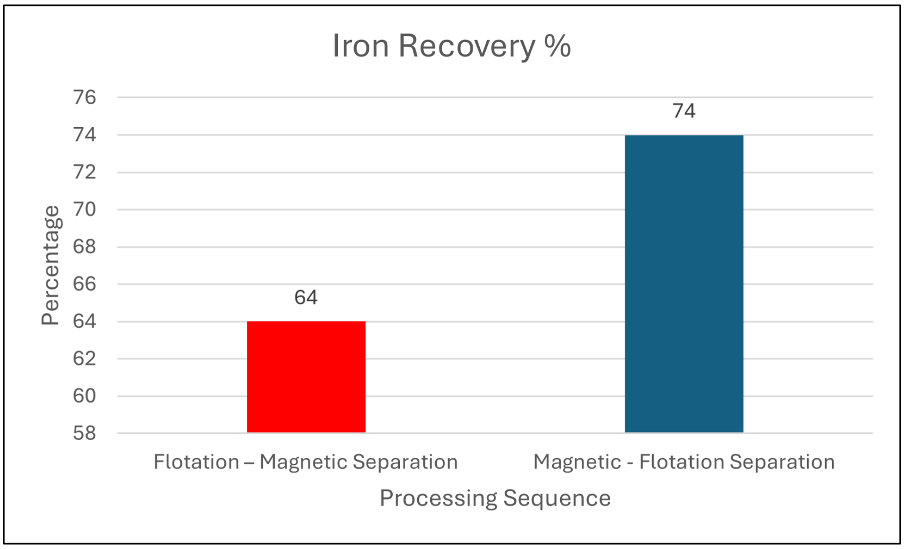


Figure 3.8. Iron Recovery Drobe et al. [2021]

iv. **Iron Content**

The iron content in the concentrate was similar in sequences: 60% for F-M and 59.8% for M-F as shown on Figure 3.9 This suggests that the two sequences produce comparable quality iron concentrates, but MF offers higher iron recovery

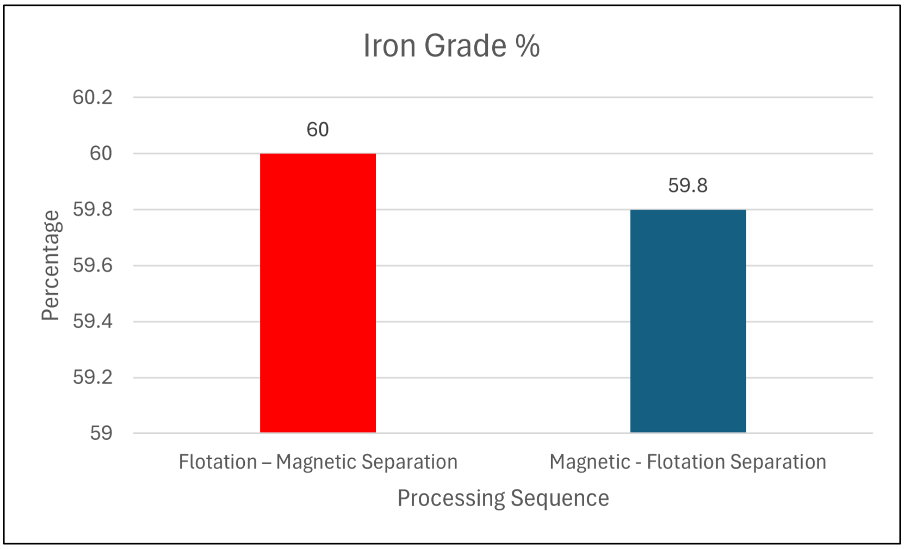


Figure 3.9. Iron Grade Drobe et al. [2021]

Magnetic - Flotation Separation Tailings

In the M-F sequence, the tailings contained 44.6% copper and 21.4% iron, indicating significant losses in the magnetic fraction Drobe et al. [2021]. This suggests that magnetic separation before flotation leads to higher iron recovery but results in substantial copper losses.

Conclusion for Case B

The Flotation followed by Magnetic Separation resulted in higher copper recovery of up to 66.2% compared to the Magnetic Separation followed by Flotation sequence of 44.2%, making it more suitable for copper recovery. However, the M-F sequence was better for iron recovery, yielding 74% compared to 64% for the F-M sequence. Overall, the F-M sequence is better suited for copper recovery, while the M-F sequence is more effective for iron recovery. The decision on which sequence to use depends on the relative importance of recovering copper or iron from the tailings.

3.3.3 Case C: Heap Bioleaching of Tailings

Source and Characterization of the tailings

Xiao-dong et al. [2017] evaluated the bioleaching process of copper flotation tailings sourced from the Lualo tailings dam in Zambia and lump ores from the Dexing Copper Mine in China as a framework sample. The lump ores provide physical and chemical support that enhances the bioleaching efficiency of the fine-grained tailings, ultimately improving copper recovery rates. This study aimed to assess copper recovery efficiency through bioleaching techniques, emphasizing the interactions between fine-grained tailings and lump ores, facilitated by mixed microbial cultures. Composition The tailings from the Lualo tailings dam showed a fine-grained texture, with 48% of the material being smaller than 75 μm Xiao-dong et al. [2017]. The chemical composition of the tailings and lump ores is summarized in Table 3.6

Component	Tailings (wt%)	Lump Ores (wt%)
Cu	0.19	0.58
Fe	19.73	2.86
S	2.25	0.8
Ca	3.27	4.39
Na	1.25	0.63
Al	4.60	4.44
K	1.40	1.46
Mg	–	1.58

Table 3.6. Chemical Composition of tailings Xiao-dong et al. [2017]

Copper Phase Analysis

The copper phase analysis indicated a mixture of copper oxides and sulphides, with primary copper sulphide being the most prevalent phase in the tailings as shown in Table 3.7.

Component	Tailings (wt%)	Lump Ores (wt%)
Free Copper Oxide	29.47	9.84
Combined Copper Oxide	6.32	1.64
Secondary Copper Sulphide	28.95	52.46
Primary Copper Sulphide	35.26	36.06

Table 3.7. Mineralogical composition of Copper Phase Xiao-dong et al. [2017]

Methodology

The bioleaching experiments were conducted in a custom-designed heap reactor, constructed from high-density polyethylene (HDPE) with dimensions of 2.0 m × 0.7 m × 1.7 m

Xiao-dong et al. [2017]. The heap structure included a base layer of quartz sand, upon which the ore heap, comprising lump ores and tailings, was established as shown in Figure 3.10.

A mixed culture of microorganisms, primarily Acidithiobacillus and Leptospirillum, was employed to promote bioleaching. Ferric ions (Fe^{3+}) played a critical role in copper extraction through the following mechanisms:

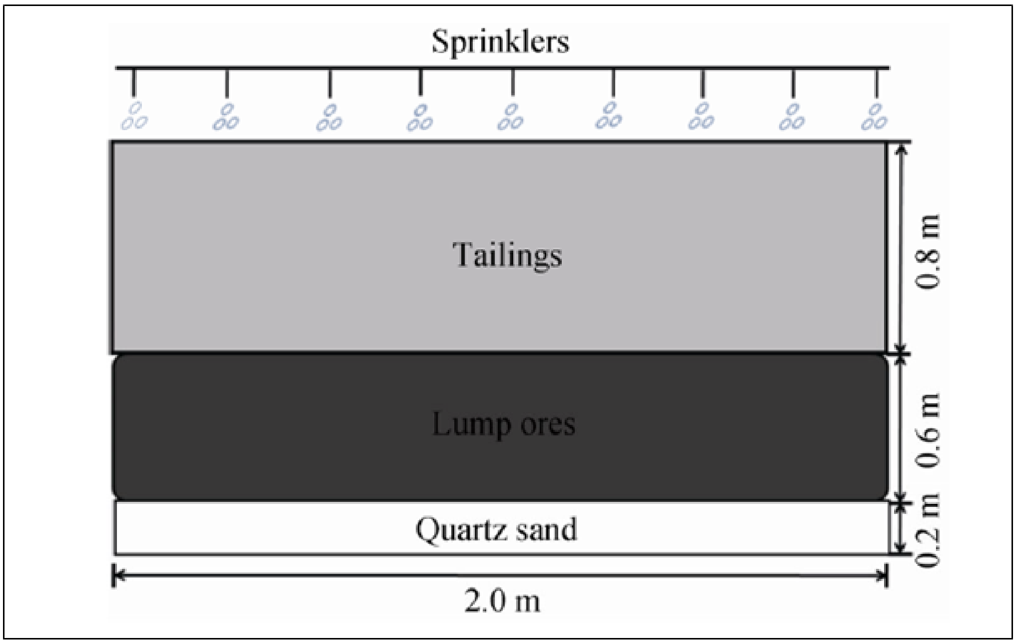


Figure 3.10. Schematic of the heap construction and loading Xiao-dong et al. [2017]

i. **Oxidizing Agent**

Ferric ions serve as oxidizing agents, facilitating the conversion of copper sulphides into soluble copper species. This oxidation is essential for the solubilization of copper from tailings and lump ores.

ii. **Leaching Mechanism**

Microorganisms oxidize ferrous ions Fe^{2+} to ferric ions Fe^{3+}. The ferric ions then react with copper sulphide minerals, dissolving copper ions into the leachate solution, as illustrated by the reaction below:

$$Cu_2S + 4\,Fe^{3+} \longrightarrow 2\,Cu^{2+} + 4\,Fe^{2+} + S$$

The operation involved spraying sulfuric acid over the heap, allowing the solution to percolate through the material Xiao-dong et al. [2017]. The critical experimental conditions were:

i. pH Range of 1.8 to 2.5

ii. Temperature Range of 5°C to 40°C

iii. Leaching Duration of 210 days

Results

The bioleaching process was divided into four phases based on the concentration of ferric iron and the redox potential of the solution as shown in Figure 3.11.

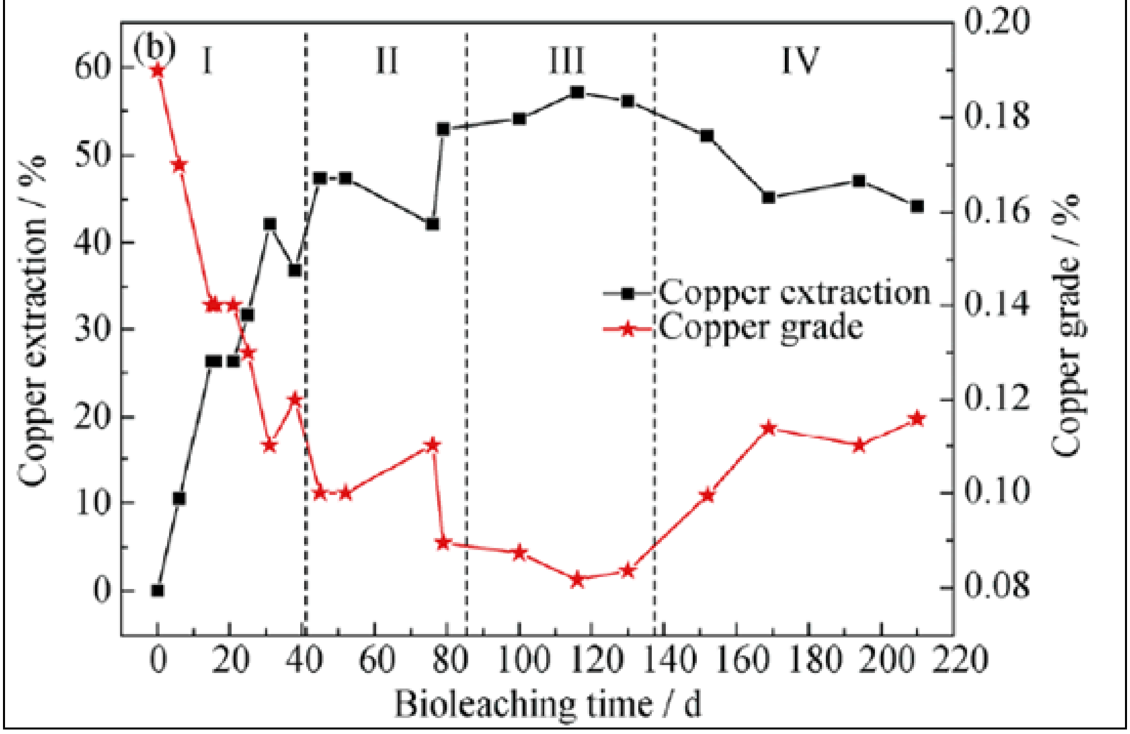


Figure 3.11. Copper grade and extraction of ore residues during the heap bioleaching process Xiao-dong et al. [2017]

i. **Phase I (Day 1-41)**

Ferric iron concentration increased rapidly, with copper recovery from the tailings reaching 42.11%. A layer of copper sulphate and jarosite $KFe_3(SO_4)_2(OH)_6$ began to form, inhibiting further copper extraction.

ii. **Phase II (Day 41-86)**

Copper extraction continued, with a recovery rate of 52.9% and a steady increase in ferric iron levels.

iii. **Phase III (Day 86-137)**

Despite a decrease in ferric iron concentration, copper extraction increased to 57.10%, although the process slowed due to jarosite formation Xiao-dong et al. [2017].

iv. **Phase IV (Day 137-210)**

No further copper recovery from the tailings was observed as microbial activity declined.

Conclusion for Case C

This case study demonstrates the feasibility of heap bioleaching for extracting copper from fine-grained flotation tailings by utilizing lump ores as a supportive framework. The total copper recovery rate from the tailings was 57.10%. The formation of jarosite during the later stages of bioleaching significantly hindered metal recovery, indicating the need for further optimization to enhance microbial activity and mitigate passivation effects Xiao-dong et al. [2017].

3.3.4 Case Comparisons

The second part of the results analysis focuses on evaluating the presented cases to determine which process is more feasible or scalable based on key performance indicators (KPIs). These KPIs include process efficiency, and duration of the process, which are crucial for assessing the viability of residual mineral recovery.

Efficiency

The efficiencies for the three cases were compared, in Figure 3.12. Case A showed the highest efficiency of 73.7%, followed by Case B 66.2%. Case C had a lower efficiency of 57.1%. Since the primary objective is to maximize the recovery of residual copper minerals and mitigate potential Acid Mine Drainage risks, froth flotation emerges as the most effective method for this specific KPI.

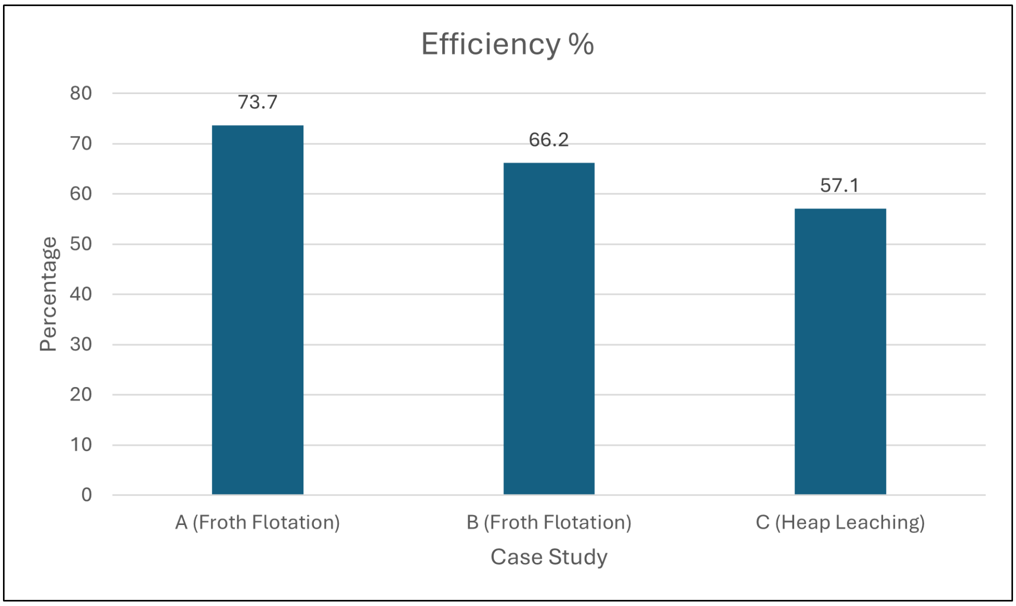


Figure 3.12. Comparison between different process efficiencies

Processing Duration

The duration required to process a fixed quantity of tailings for each method was analysed. The timeframes for the same quantity of tailings 1568 kg are compared below.

Heap Leaching (Case C)

Heap leaching lasted approximately 137 days to recover copper from the tailings. The following calculation outlines the mass and time required for processing in a custom-designed HDPE unit:

i. **Volume of tailings in the reactor:**

   $0.8\,\mathrm{m} \times 2\,\mathrm{m} \times 0.7\,\mathrm{m}{=}1.12m^3$

ii. **Density of tailings:**

   $1.4\mathrm{g}/cm^3{=}1400\mathrm{kg}/m^3$ (Sracek et al. [2010])

iii. **Mass of tailings:**

   $1400\,\mathrm{kg/m^3} \times 1.12\,\mathrm{m^3} = 1568\,\mathrm{kg}$

Therefore, it took 137 days to process 1568 kg of tailings using heap leaching.

Froth Flotation (Cases A and B)

For froth flotation, parameters from Case A were used to evaluate the processing time:

i. **Flotation cell capacity:**

2.5L=2500cm^3

ii. **Pulp density:**

An average pulp density of 1.2g/cm^3 was used from the provided information.

iii. **Mass of tailings in flotation cell:**

Mass of copper concentrate:

$2500\,\mathrm{cm}^3 \times 1.2\,\mathrm{g/cm}^3 = 3000\,\mathrm{g}$

iv. **Mass of water in flotation cell:**

$2500\,\mathrm{cm}^3 \times 1\,\mathrm{g/cm}^3 = 2500\,\mathrm{g}$

vi. **Mass of tailings:**

$3000\,\mathrm{g} - 2500\,\mathrm{g} = 500\,\mathrm{g}$

vii. **Flotation time:**

15 minutes to process 500 g of tailings in the 2.5 L flotation cell.

viii. **Total time to process 1568 kg:**

$$\left(\frac{1568\,\mathrm{kg}}{0.5\,\mathrm{kg}}\right) \times (15\,\mathrm{minutes}) = \frac{47{,}040\,\mathrm{minutes}}{60} = 784\,\mathrm{hours}$$

Assuming 90% availability and utilization of the flotation machine:

(a) **Effective operating time per day:**

$24\,\mathrm{hours/day} \times 0.9 \times 0.9 = 19.44\,\mathrm{hours}$

(b) **Total days to process 1568 kg:**

(784hours/19.44hours)=40.3days

Therefore froth flotation (Case A) would take 41 days to process the same quantity of tailings using a 2.5 L Denver cell.

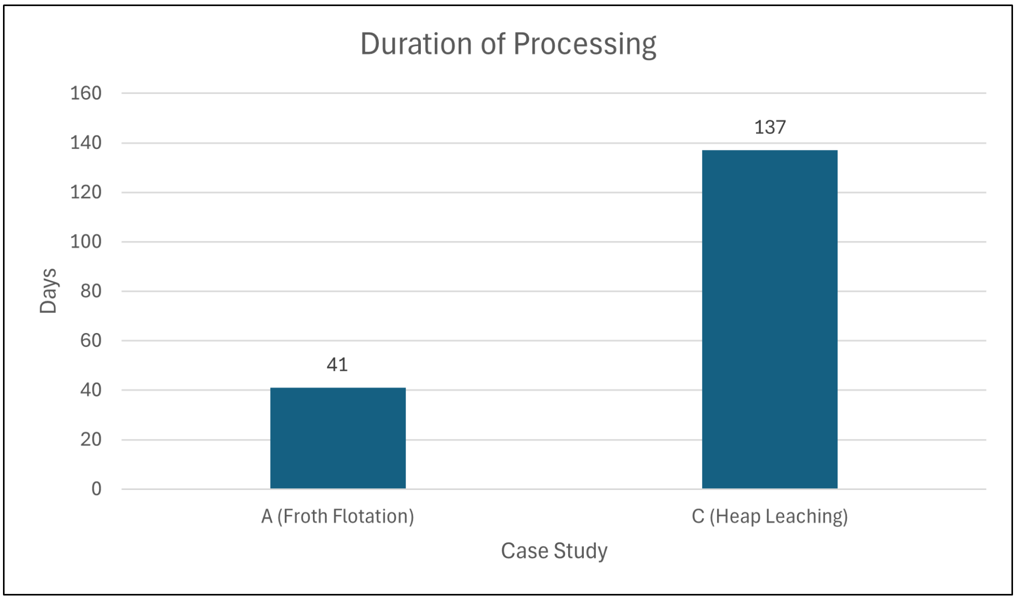


Figure 3.13. Comparison between different processing durations

From Figure 3.13, it is evident that froth flotation is a significantly faster process compared to heap leaching, requiring only 41 days to process the same quantity of tailings, that would require 137 days for heap leaching.

Conclusion

Based on the comparisons, froth flotation emerges as the more favourable and feasible method in terms of efficiency and duration. It offers faster processing times and higher recovery rates, making it a more practical option for valorising copper tailings, especially when the goal is maximising copper recovery. However, heap leaching should not be completely disregarded. It demonstrates greater efficiency in processing tailings containing copper oxides and low-grade sulfidic tailings, where froth flotation is less efficient. Heap leaching may still be a viable and cost-effective recovery method for scenarios where oxide–dominated tailings or low-grade tailings are the primary materials. Therefore, both processes have advantages, depending on the mineralogical composition of the tailings being treated.

3.4 Results and Analysis of Tailings Reduction Techniques

3.4.1 Case A: Utilisation of Copper/Zinc Mine Tailings in Geopolymers Production

Source and Characterization of the tailings

The mine tailings investigated in this study by Paiva et al. [2019] were sourced from copper and zinc mining operations. The mine tailings lacked sufficient aluminosilicates, making them unsuitable as a primary binder precursor for geo-polymerisation. However, their composition still allowed them to function effectively as a fine aggregate in geopolymer formulations. The relevant oxide components are listed in Table 3.8. These values indicate that while the tailings contain silica, the alumina content is low, which limits their reactivity in the geo-polymerisation process.

Component	Percentage (%)
Al_2O_3	6.41
SiO_2	25.16

Table 3.8. Aluminosilicates Composition Paiva et al. [2019]

Methodology

Geopolymer Formulations

Metakaolin (MK) was used as the primary binder precursor due to its high reactivity and ability to enhance the mechanical strength of geopolymers. Various formulations were tested, with different proportions of mine tailings replacing MK:

i. 100% MK with 0% MT

ii. 50% MK with 50% MT

iii. 38% MK with 62% MT

Alkaline Activators

Sodium metasilicate was used as the alkaline activator in the geopolymers. These activators are critical in facilitating the geo-polymerisation process.

Curing Conditions

Curing was conducted in a controlled environment at 20 ± 5°C with 65 ± 5% relative humidity. Some samples were also cured at 50°C, but excessive curing at higher temperatures for extended periods was found to reduce compressive strength due to water evaporation and silica coagulation Paiva et al. [2019].

Results and Analysis

Compressive Strength

The formulation with 100% MK achieved a compressive strength of 32 MPa, demonstrating the superior mechanical performance of MK-based geopolymers. When 50% MK was replaced with mine tailings (50% MT), the compressive strength dropped to 22 MPa as shown in Figure 3.14. Further replacing MK with 62% MT resulted in a significant strength reduction to 14 MPa, indicating that the non-reactive nature of MT negatively impacted the strength.

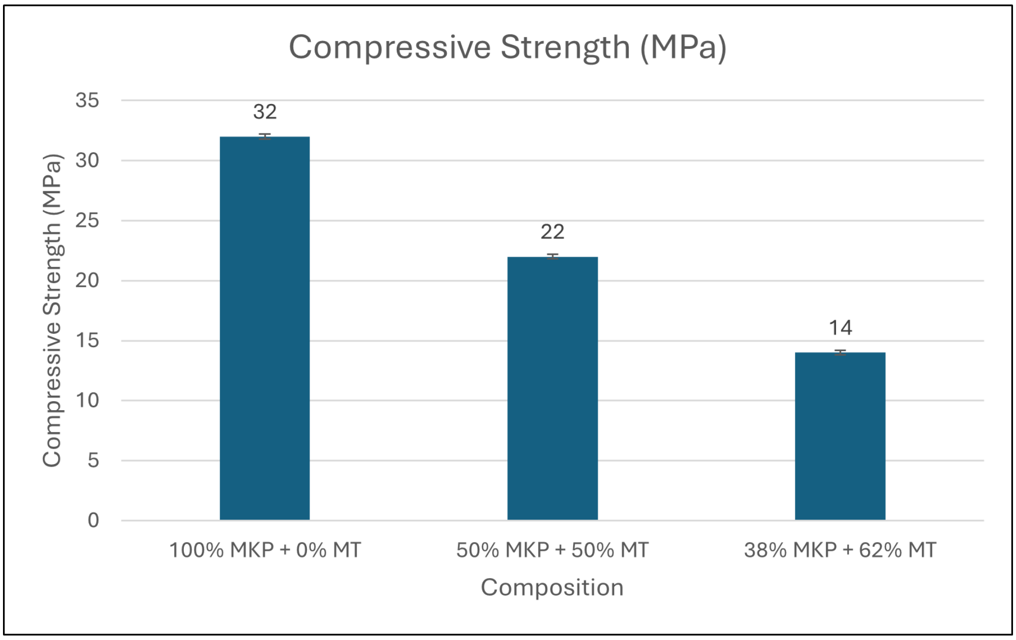


Figure 3.14. Compressive Strength of MK–based geopolymers with different contents of mine tailing Paiva et al. [2019]

Bulk Density

The addition of mine tailings increased the bulk density of the geopolymer formulations, with the highest bulk density observed at 50% MT content in Figure 3.15. However, this increase in bulk density also contributed to higher torque and viscosity during mixing, complicating the material's processing.

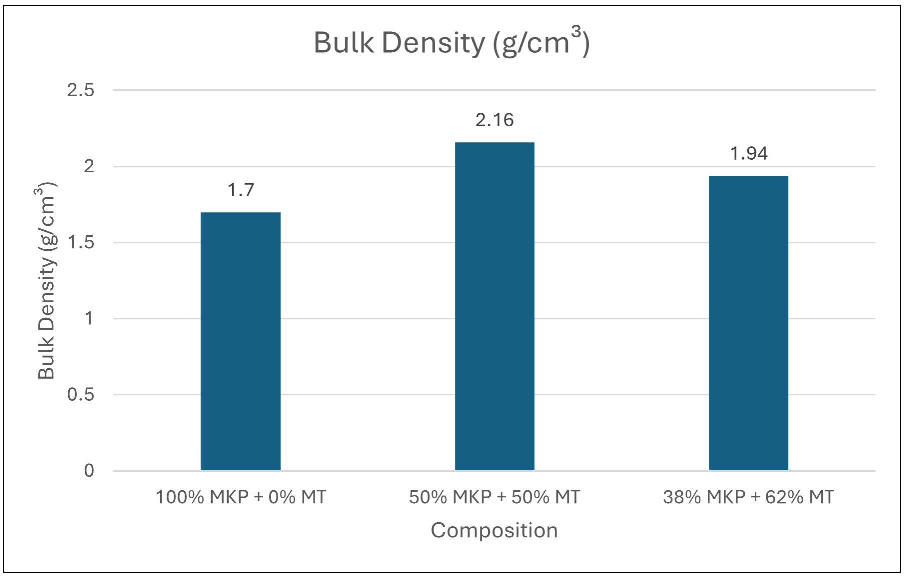


Figure 3.15. Bulk Density of MK-based geopolymers with different contents of mine tailing Paiva et al. [2019]

Torque and Viscosity

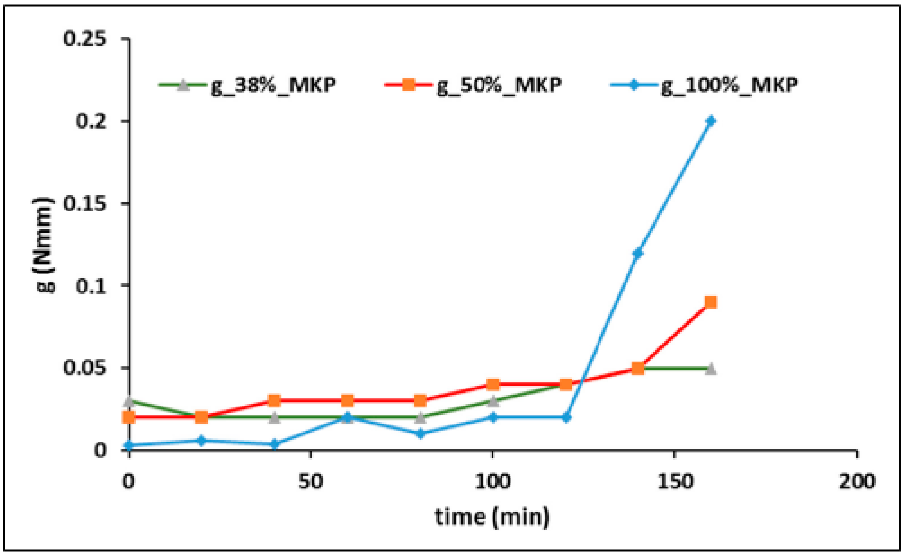


Figure 3.16. Variation of g parameter values with MKP content Paiva et al. [2019]

As the mine tailings content increased, the geopolymer slurry's torque (mixing resistance) and viscosity of the geopolymer slurries also increased as shown in Figure 3.16. This rise in torque and viscosity, caused by the higher solids content, made the geopolymer mixtures stiffer and more difficult to handle. Controlling these factors is essential to ensure uniform mixing and effective handling during the production of geopolymer materials.

Geochemical Analysis and Leaching Tests

A static leaching test was conducted to evaluate the durability and chemical resistance of the geopolymers.

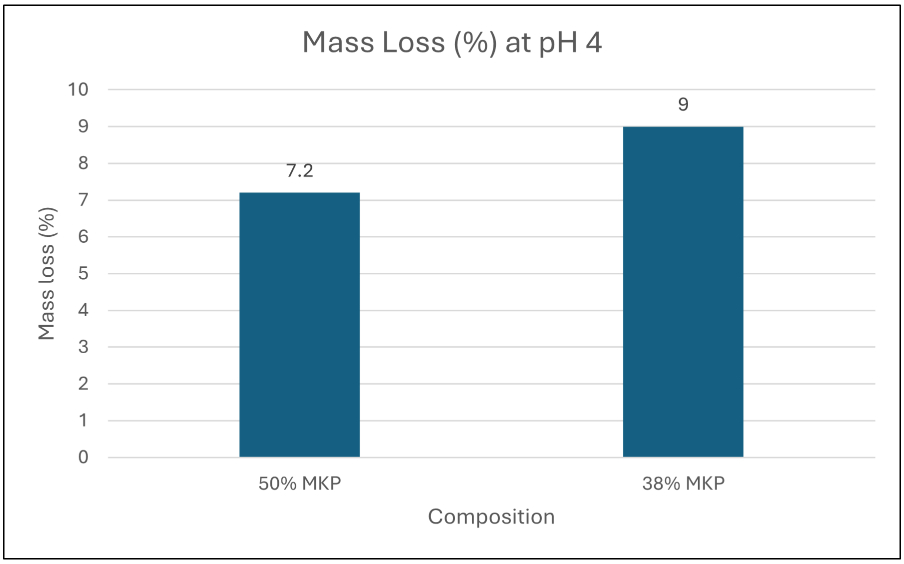


Figure 3.17. Mass loss after 40 days in pH 4 Paiva et al. [2019]

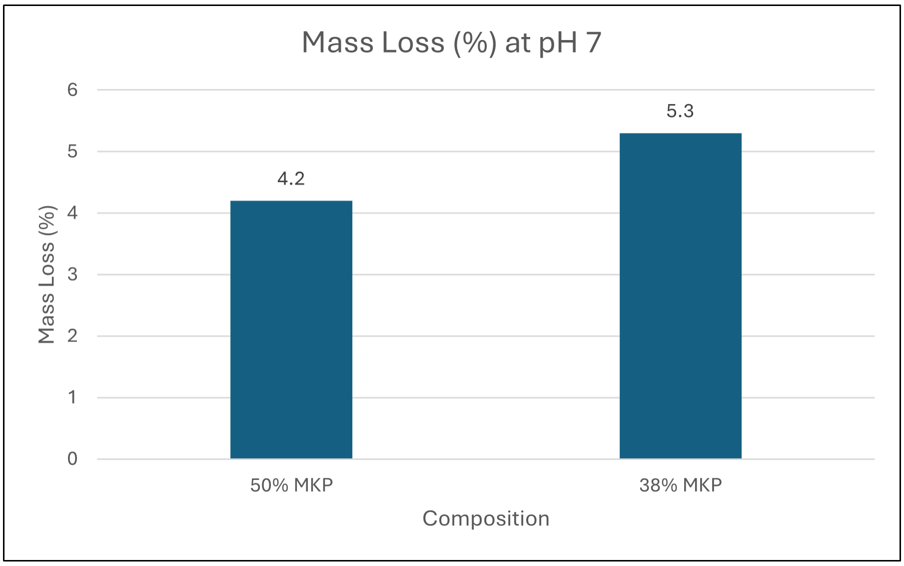


Figure 3.18. Mass loss after 40 days in pH 7 Paiva et al. [2019]

Samples were soaked in solutions with pH values of 4 in Figure 3.17 and pH 7 in Figure 3.18 for 40 days. The leach tests assessed the efficiency of metal immobilization by the geopolymer matrix, with nitric acid used to maintain the pH of the solutions. The results revealed that the mass loss due to leaching was lower than the reference values for mine tailings. This indicates that the geo-polymerisation process effectively immobilises harmful metals, even with reduced binder content.

Conclusion for Case A

This study demonstrates that while the adding mine tailings (MT) as a non-reactive aggregate increases bulk density, it also reduces compressive strength and affects the workability of the geopolymer mixtures. A higher MT content leads to increased torque and viscosity, complicating the mixing and casting processes Paiva et al. [2019]. The geochemical analysis suggests that the geopolymer matrix can effectively immobilise heavy metals, contributing to the material's durability and environmental benefits. However, achieving optimal mechanical properties requires careful control of the composition and curing conditions. The reduced compressive strength observed with higher MT content limits the suitability of such formulations for structural applications, though they may still be viable for use in non-load-bearing applications or mine refilling, where a compressive strength of 5 MPa is sufficient Paiva et al. [2019]. In conclusion, successful geo-polymerisation with copper/zinc mine tailings requires a balance between utilizing tailings as aggregates and maintaining sufficient binder content (MK or BFS) to achieve the desired mechanical and durability properties

3.4.2 Case B: Utilization of Mine Tailings in Ceramic Production

Source and Characterization of the tailings

Paiva et al. [2021] did another mine tailings analysis using tailings from a copper mine in southern Portugal. The mineral composition of the tailings was determined through X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) analyses. The results are presented in Table 3.9 revealed a low content of Al_2O_3, limiting the tailings' potential for alkali activation in geo-polymerisation Paiva et al. [2021].

Element	Percentage (%)
Al_2O_3	6.4
SiO_2	25.2
SO_3	26.2
K_2O	0.4
CaO	0.8
Fe_2O_3	19.2
Cu	0.2
Zn	0.3

Table 3.9. X–ray fluorescence. Major elements (%) Paiva et al. [2021]

Particle Size Distribution

The particle size distribution of the tailings ranged from $2\,\mu$m to $200\,\mu$m, with 26% of particles exceeding $63\,\mu$m. The finer fraction aligns with the presence of quartz and clay minerals, which are commonly utilized in ceramic applications.

Methodology

Mechanical Properties in Ceramic Applications

Integrating mine tailings (MT) into ceramic roof tile formulations involved various mechanical tests to evaluate performance. The tailings were introduced in different proportions into a base formulation of yellow clay, red clay, and sand as shown in Table 3.10. Differential Thermal Analysis (DTA) indicated that an exothermic reaction commenced at 600°C. The decomposition of pyrite occurred between 600°C and 800°C, releasing SO_2 and SO_3 gases, which can form sulfuric acid upon contact with water Paiva et al. [2021].

Composition	Yellow Clay (%)	Red Clay (%)	Sand (%)	MT (Mine Tailings) (%)
C_0%MTP	60	30	10	–
C_5%MTP	55	30	10	5
C_10%MTP	50	30	10	10
C_20%MTP	40	30	10	20

Table 3.10. Ceramic roof tiles compositions under test Paiva et al. [2021]

Results and Analysis

The results, in Table 3.11, illustrate the flexural strength at varying firing temperatures for compositions with different MT percentages.

Composition	850°C (MPa)	950°C (MPa)	1050°C (MPa)	1150°C (MPa)	1200°C (MPa)
C_0%MTP	8.9 ± 0.1	15.3± 1.4	20.4± 0.6	29.6 ± 1.5	29.9 ± 1.3
C_5%MTP	10.5 ± 1.0	15.8 ± 0.8	20.1± 0.9	–	–
C_10%MTP	9.0 ± 0.2	18.2 ± 0.1	23.2 ± 0.6	29.5± 1.3	20.3 ± 1.4
C_20%MTP	15.5 ± 0.5	19.9 ± 0.1	27.5 ± 0.1	20.5 ± 1.0	12.6 ± 0.6

Table 3.11. Flexural strength evolution with the increase on firing temperature for all compositions Paiva et al. [2021]

Figure 3.19 shows that the highest flexural strength was observed in the C_20%MT composition at 1050°C, indicating that increased MT content enhances the mechanical strength of ceramic materials, particularly at lower firing temperatures.

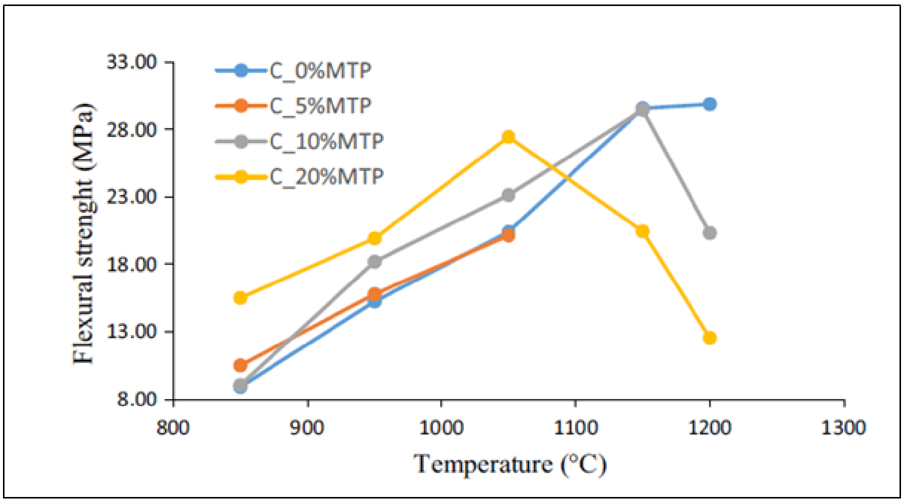


Figure 3.19. Flexural strength behaviour with the increase of firing temperature of ceramic compositions Paiva et al. [2021]

Effect of Mine Tailings

Figure 3.19 illustrates a trend of increasing the percentage of mine tailings which generally improves the flexural strength of the ceramic material, particularly at lower firing temperatures. This enhancement is attributed to the higher iron content in the tailings, which acts as a flux during firing Paiva et al. [2021]. Fluxes lower the material's melting temperature, promoting the formation of a glassy phase that binds the particles together, thus improving mechanical properties such as strength.

Weight Loss Analysis

The weight loss of samples during firing was analysed, as summarized in Table 3.12.

Composition	850°C	950°C	1050°C	1150°C	1200°C
$C_{0\%}$ MTP	3.98 ± 0.4	4.59 ± 0.06	4.70 ± 0.02	4.72 ± 0.01	4.97 ± 0.05
$C_{5\%}$ MTP	4.63 ± 0.15	4.88 ± 0.03	5.41 ± 0.08	–	–
$C_{10\%}$ MTP	4.85 ± 0.14	5.80 ± 0.03	6.29 ± 0.06	5.92 ± 0.09	6.03 ± 0.09
$C_{20\%}$ MTP	5.52 ± 0.05	7.15 ± 0.02	7.60 ± 0.02	7.33 ± 0.12	7.46 ± 0.10

Table 3.12. Weight loss behaviour with the increase of firing temperature to all compositions Paiva et al. [2021]

The baseline composition showed the lowest weight loss percentages across all temperatures. The increase in weight loss with higher percentages of mine tailings indicates the decomposition of certain minerals, such as sulphates, during firing.

Water Absorption Analysis

Composition	850°C	950°C	1050°C	1150°C	1200°C
C_0%MTP	17.4 ± 0.3	16.3± 0.2	12.8± 0.2	4.5 ± 0.4	7.4 ± 0.3
C_5%MTP	17.4 ± 0.6	16.9 ± 0.2	12.1± 0.6	–	–
C_10%MTP	17.0 ± 0.2	14.5 ± 0.2	13.6 ± 0.4	12.5± 0.51	16.1 ± 0.9
C_20%MTP	14.5 ± 0.4	14.4 ± 0.3	9.5 ± 0.4	11.7 ±0.4	19.1 ± 1.5

Table 3.13. Water absorption behaviour with the increase of firing temperature Paiva et al. [2021]

In Table 3.13 C_0%MTP composition shows the lowest water absorption at 1150°C of 4.5%. C_20%MTP composition shows the lowest water absorption at 1050°C (9.5%) but increases notably at 1200°C (19.1%), indicating a strong impact of high mine tailings content on water absorption at higher temperatures.

Conclusion for Case B

The study concludes that incorporating mine tailings into ceramic formulations significantly enhances mechanical properties, particularly compressive strength, while reducing the required firing temperature. The optimal 20% MT ceramic formulation demonstrated the highest compressive strength at lower firing temperatures, decreasing energy costs and economic benefits. Furthermore, the sulphur gas released during the decomposition of sulphates can be managed by redirecting kiln emissions to a condensation chamber, producing an acid solution as a by-product and minimising environmental impact. Increasing the mine tailings content impacts water absorption, particularly at higher firing temperatures.

3.4.3 Case Study C: Utilization of Copper Mine Tailings in Hollow Concrete Blocks

Source and Characterization of the tailings

The copper mine tailings investigated in this study by Ndikumana et al. [2024] were from Kitwe Tailings, Zambia. Their fineness is a crucial role in the hydration process which is important in the cement industry. Table 3.14 provides the physical characteristics of the tailings.

Physical Property	Copper Mine Tailings
Specific Gravity	1.85
Water Absorption (%)	2.93
Moisture Content (%)	0.80
Bulk Density (g/cm^3)	1.45
Silt Content (%)	2.93
Fineness	2.46

Table 3.14. Physical properties of copper mine tailings Ndikumana et al. [2024]

Other Materials Used

In addition to copper mine tailings, the other materials used in this study were:

i. SUPASET CEM/A-LL 42.5 R, cement produced by Chilanga Cement Zambia, conforming to ZS EN: 197-1. This limestone Portland cement (Type II) is characterised by high performance and adaptability.

ii. Fine Aggregate from quarry dust

iii. Coarse Aggregate from Crushed stone

Chemical Analysis

X-ray fluorescence (XRF) was used to conduct chemical analysis on the copper mine tailings and cement. The results, in Table 3.15, indicate that the copper mine tailings contain higher amounts of SiO_2, CaO, Fe_2O_3, and Al_2O_3, when compared to the cement. These oxides represent around 60% of the tailings' composition. The tailings have a lower lime content (CaO) than cement, an important element that could affect its hydration behaviour

Component	Cement (%)	Copper Mine Tailings (%)
SiO_2	18.74	37.87
Al_2O_3	3.86	9.79
CaO	52.33	8.94
Fe_2O_3	2.99	2.49
SO_3	3.40	0.32
K_2O	0.49	5.47
MgO	–	4.28
MnO	0.06	0.31
TiO_2	0.33	0.68
Cu	0.03	0.41
Zn	0.003	0.003
Ni	0.04	0.04

Table 3.15. Chemical analysis of Cement and Copper mine tailings Ndikumana et al. [2024]

Methodology

To improve the contribution of copper mine tailings to the hydration process, further milling in the ball mill was done to increase their fineness. The mix designs were developed using the Design of Experiment (DOE) method, and hollow concrete blocks were prepared according to IS 2185-2 (1983), with concrete grade M5 Ndikumana et al. [2024]. Six different mix designs were tested, with copper mine tailings replacing cement in proportions from 0% to 50% as shown in Table 3.16.

Block Sample Codes	Cement (Kg/m^3)	Copper Mine Tailings (Kg/m^3)	Fine Aggregate (Kg/m^3)	Coarse Aggregate (Kg/m^3)	Water (Kg/m^3)
CBCMT 0%	370.37	0	1664.67	184.96	200
CBCMT 10%	333.33	37.04	1664.67	184.96	200
CBCMT 20%	296.30	74.07	1664.67	184.96	200
CBCMT 30%	259.26	111.11	1664.67	184.96	200
CBCMT 40%	222.22	148.15	1664.67	184.96	200
CBCMT 50%	185.19	185.18	1664.67	184.96	200

Table 3.16. Mix designs of cement with copper mine replacement ratio Ndikumana et al. [2024]

Compressive Strength

As shown in Figure 3.20, the hollow concrete blocks' compressive strength was tested at intervals of 7, 14, 21, and 28 days a The target compressive strength was set at 5 MPa for blocks after 28 days of curing.

i. CBCMT 0%, CBCMT 10%, and CBCMT 20% met the strength target after 28 days, with CBCMT 20% achieving the highest strength at 28 days of 5.32 MPa.

ii. Blocks containing higher proportions of mine tailings CBCMT 30%, CBCMT 40%, and CBCMT 50% showed lower compressive strengths but were expected to achieve the target strength with further curing, as the tailings require longer time to complete the hydration process Ndikumana et al. [2024].

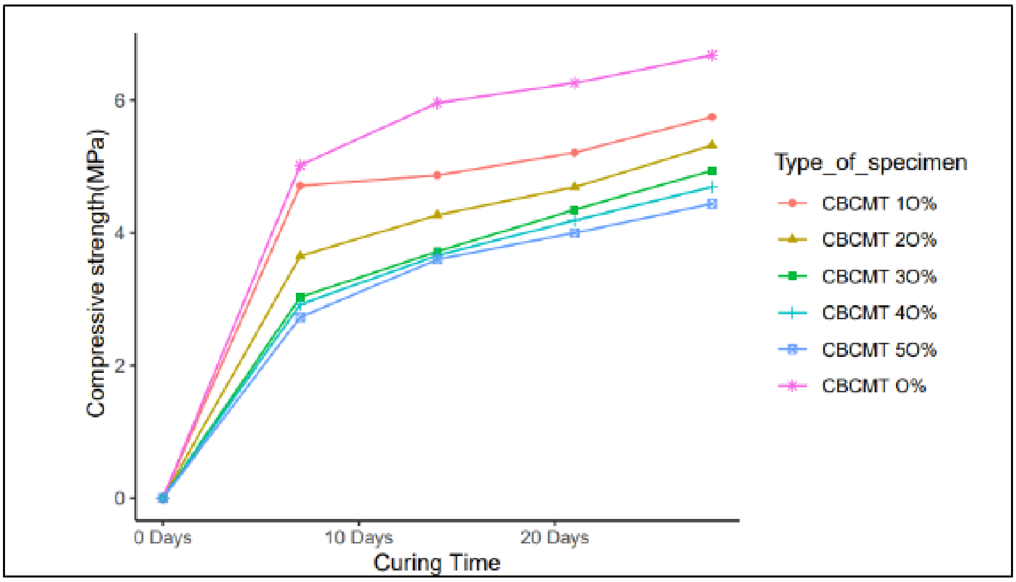


Figure 3.20. Compressive strength of hollow concrete blocks Ndikumana et al. [2024]

Water Absorption

Water absorption tests were conducted after 28 days, following IS 2185-1 standards. The results showed a low water absorption rate for all specimens, with the replacement of copper mine tailings slightly reducing water absorption, as shown in Figure 3.21. The CBCMT 20% block demonstrated the best performance, with the lowest water absorption.

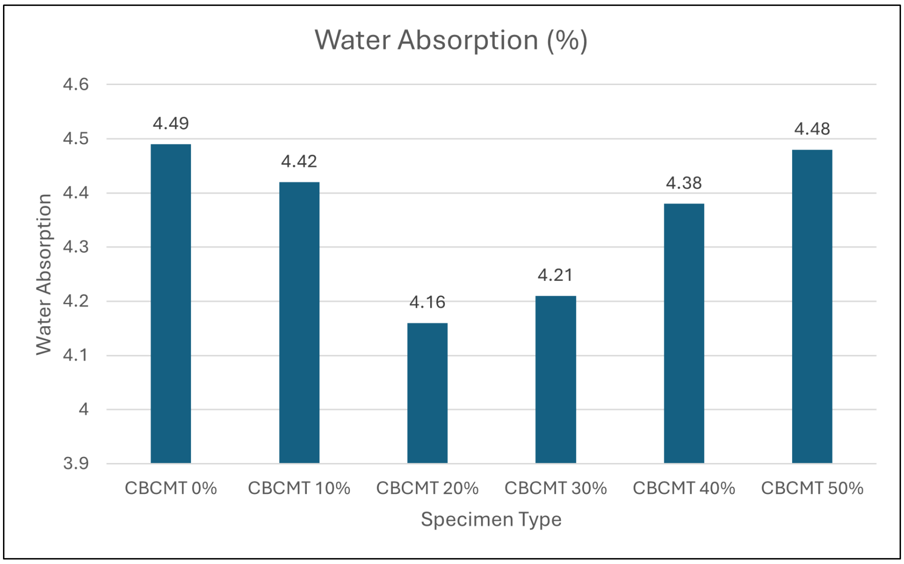


Figure 3.21. Water absorption of Hollow concrete block specimens Ndikumana et al. [2024]

Acid Attack Resistance

Immersing samples tested the acid resistance of the hollow concrete blocks in a 5% HCl solution for 28 days. Figure 3.22 shows that the mass loss of the blocks decreased as the copper mine tailing replacement increased, confirming that mine tailings improved the acid resistance of the blocks.

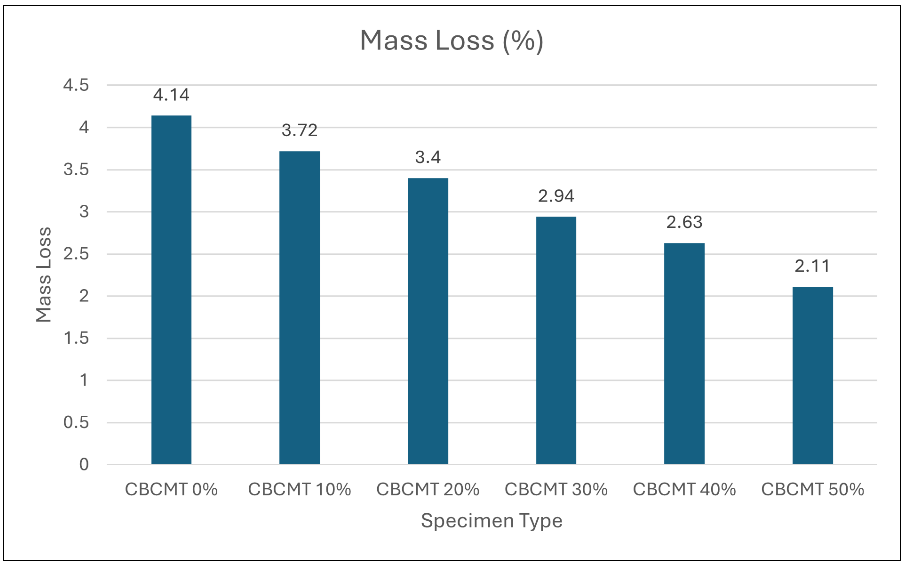


Figure 3.22. Acid attack resistance of Hollow concrete block specimens Ndikumana et al. [2024]

Conclusions for case C

This case study demonstrates that copper mine tailings can effectively replace some of the cement in producing hollow concrete blocks, offering environmental and durability benefits. The CBCMT 20% mix design achieved a compressive strength at 28 days of 5.32 MPa higher than the target of 5MPa and performed best in water absorption tests. Higher proportions of copper mine tailings improved the acid resistance of the blocks, with the CBCMT 50% specimen showing the most minor mass loss during the acid attack test. Additionally, all tested blocks met acceptable water absorption and heavy metal leaching criteria, making copper mine tailings a viable alternative to traditional cement in concrete applications.

3.4.4 Case Comparisons

The second part of the results analysis focuses on evaluating the presented cases to determine the most feasible process, based on three key performance indicators (KPIs); compressive strength, acid leaching, and water content. These parameters are critical in achieving durable and environmentally sustainable products from tailings reduction techniques. It is important to note that while these KPIs provide valuable insights, the feasibility of each method also depends on the specific mineralogy of the tailings being treated.

Compressive Strength

Compressive strength is crucial for the structural integrity of the final product. It measures the material's ability to bear loads without failure. Since each case had different targets for compressive strength, the achieved strength is presented as a percentage of the target value as shown in Table 3.17 Compressive strength analysis. This allows for an easier comparison across the three different methods

Case Study	Achieved (MPa)	Target (MPa)	Percentage (%)
A (Geopolymer)	22.0	32.0	68.9
B (Ceramic, 1200°C, firing temperature)	27.5	29.9	92.0
B (Ceramic, 1050°C, firing temperature)	27.5	20.4	134.8
C (Brick)	5.32	6.5	81.8

Table 3.17. Comparisons of Compressive strength of samples

Figure 3.23 shows that case B had the best results in terms of compressive strength, with two critical variations observed. At a firing temperature of 1050°C, the ceramic containing 20% mine tailings outperformed the standard ceramic, achieving an improvement of 34.8% in compressive strength. However, the highest compressive strength for the standard ceramic was obtained at a firing temperature of 1200°C, which was then compared to the maximum strength reached by the 20% mine tailings sample at 1050°C.

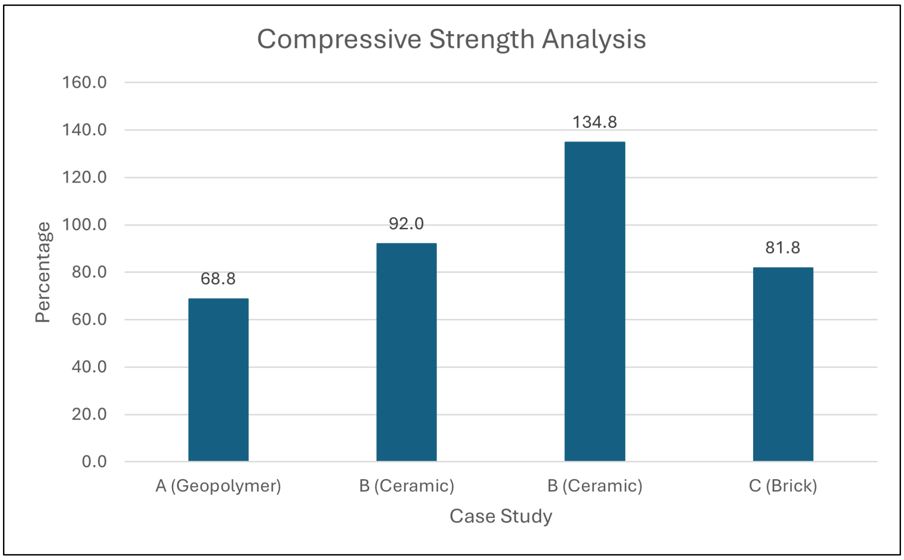


Figure 3.23. Compressive strength Analysis

This comparison yielded a relative strength of 92%, indicating that the mine tailings ceramic, even at a lower temperature, performed closely to the standard ceramic fired at a higher temperature. Although Case A (Geopolymer) showed the lowest relative performance, reaching only 68.8% of its target strength, it may still be viable for applications where lower compressive strength is acceptable.

Acid Leaching

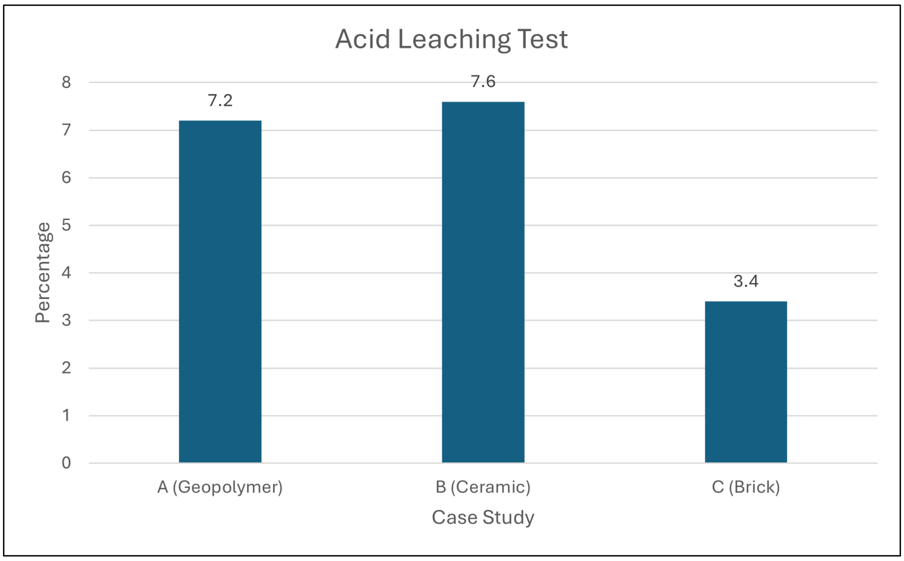


Figure 3.24. Weight loss analysis

Acid leaching tests measure the final product's ability to retain heavy metals and prevent them from leaching into the environment. This is quantified by the product's loss in mass during the leaching test, presented as a percentage in Figure 3.24.
The hollow brick (Case C) had the lowest mass loss, suggesting it was most effective at immobilizing heavy metals and preventing leaching. This makes Case C a strong option for applications where environmental protection is a priority. Case A (Geopolymer) and Case B (Ceramic) also provided satisfactory results, with mass losses of 7.2% and 7.6%, respectively.

Water Absorption

Water absorption impacts the durability and long-term performance of the final product. A lower water content is generally preferable as excessive water absorption can lead to product degradation over time. In Table 3.18, water content of each case is presented as a percentage of the standard sample.

Case Study	Sample (%)	Standard (%)	Improvement (%)
A (Geopolymer)	9.5	4.5	–111
B (Ceramic)	9.5	12.8	25.8
C (Brick)	4.16	4.49	7.4

Table 3.18. Comparisons of Samples' Water absorption

Case B (Ceramic) and Case C (Brick) outperformed their respective standard samples, absorbing less water. Case B showed a 25.8% improvement over the standard, while Case C demonstrated a 7.4% improvement. Lower water absorption indicates that both methods produce more durable and resistant materials, making them viable for practical applications regarding this parameter. Case A (Geopolymer) performed approximately 111% worse in terms of water absorption compared to the standard geopolymer. This significant increase in water absorption indicates that the sample with mine tailings absorbed more than double the amount of water compared to the standard one, which reflects a considerable reduction in performance with regard to water resistance.

Conclusion

Based on the results from the comparisons of compressive strength, acid leaching, and water absorption, Case B (Ceramic) shows the most promising overall performance, especially in its ability to incorporate mine tailings while maintaining high compressive strength and low water absorption. However, Case C (Brick) also proves effective, particularly in acid leaching, where it shows the lowest mass loss, indicating strong environmental performance. While Case A (Geopolymer) had lower compressive strength, it still demonstrated satisfactory acid leaching performance, making it potentially useful in applications with less tough structural demands. Ultimately, the most appropriate method depends on the specific requirements of the project, such as environmental considerations, mechanical strength, and the desired application of the final product.

Chapter 4

Environmental Evaluation of Valorisation of Sulfidic Copper Tailings

4.1 Introduction

The recycling and valorisation of mine tailings have gained significant attention in recent years, as discussed in Chapter 3. While experimental results promise to minimise waste and recover valuable materials, these technologies often lack a comprehensive environmental assessment. Reprocessing mine tailings does not inherently guarantee ecological benefits. While advantageous in one respect, some processes may lead to unintended consequences such as increased energy demand or the release of contaminants into the environment. Therefore, it is critical to assess whether these technologies deliver the anticipated environmental advantages, mainly when applied on a larger scale. This chapter presents three case studies that evaluate the environmental impacts of copper mining and reprocessing of copper sulfidic mine tailings through LCA. The first two case studies focus on the environmental effects of mining and tailings reprocessing. In contrast the third case study evaluates the environmental performance of reprocessing sulfidic tailings on a larger scale in the European Union. These case studies provide valuable insights into the potential environmental benefits of tailings reprocessing.

4.1.1 General Overview of Life Cycle Assessment (LCA)

Purpose and Scope

To promote the sustainable development of metal-containing products, the metals industry has widely adopted Life Cycle Assessment as a tool to evaluate and communicate the environmental impacts of its products Interational [2014]. LCA provides a comprehensive view of a product's life cycle, from raw material extraction to disposal, and is commonly used to inform decisions related to resource use, emissions, and energy consumption.

System Boundaries

A critical step in conducting an LCA is defining the system boundary, which specifies the processes included in a product system. According to ISO 14044, the system boundary is established based on the goal and scope of the study. In comparative assessments, clear system boundaries and functional unit definitions are essential, to ensure fair and consistent evaluations.

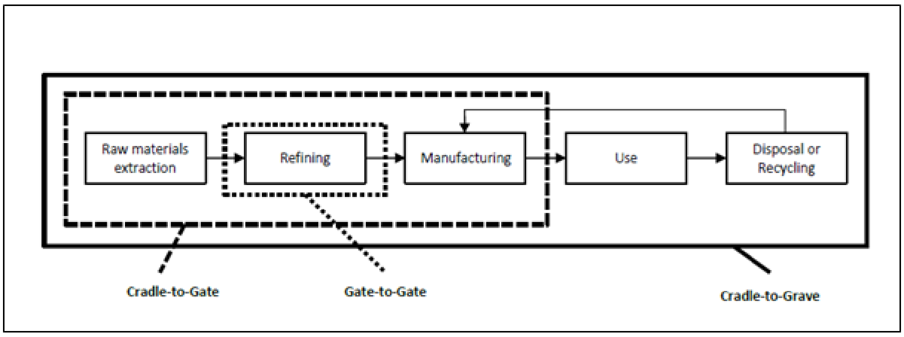


Figure 4.1. Life cycle phases for a generic product International [2014]

Life cycle stages incorporate raw material extraction, production, use, and disposal. These stages are often described using terms such as cradle-to-gate (from raw material extraction to product shipment) or cradle-to-grave (from raw material extraction to disposal) as shown in Figure 4.1.

Functional Unit

The functional unit is a crucial reference point in LCA, defined by ISO 14044 as the quantified performance of a product system for use as a reference unit International [2014]. The reference flow refers to the material required to meet the functional unit. In Case Study A, the functional unit is the production of 1 tonne of copper, while in Case Study B, it is the treatment of 1 tonne of sulfidic mine tailings.

Co-products

Many industrial processes generate multiple products, referred to as co-products, which must be accounted for in an LCA. Co-products are distinct from waste because they have economic value. For instance, sulphur dioxide is produced as a by-product in copper smelting. This sulphur dioxide can be captured and reacted with water to produce sulfuric acid, a valuable co-product, while copper remains the primary product.

4.1.2 Life Cycle Impact Assessment (LCIA)

The LCIA phase evaluates the magnitude and significance of potential environmental impacts associated with the life cycle of a product. It translates life cycle inventory data, such as emissions and resource use, into environmental impacts. These impacts are categorized into impact categories, such as global warming potential or acidification potential, which offer relative measures of environmental impact (ILCD-Handbook, 2010). Table 4.1 shows different methodologies that can be used and their countries of origin. Each methodology defines characterization models that translate environmental flows into impacts. The commonly used LCIA methodologies are TRACI, CML, and ReCiPe Interational [2014].

Analysed LCIA methodologies	Developed by	Country of origin
CML2002	CML	Netherlands
Eco-indicator 99	PRe	Netherlands
EDIP97 – EDIP2003	DTU	Denmark
EPS 2000	IVL	Sweden
Impact 2002+	EPFL	Switzerland
LIME	AIST	Japan
LUCAS	CIRAIG	Canada
ReCiPe	RUN + PRe + CML	Netherlands
Swiss Ecoscarcity 07	E2 + ESU-services	Switzerland
TRACI	US EPA	USA
MEEuP	VhK	Netherlands

Table 4.1. LCIA methodologies and their country of origin Handbook [2010]

ReCiPe Methodology

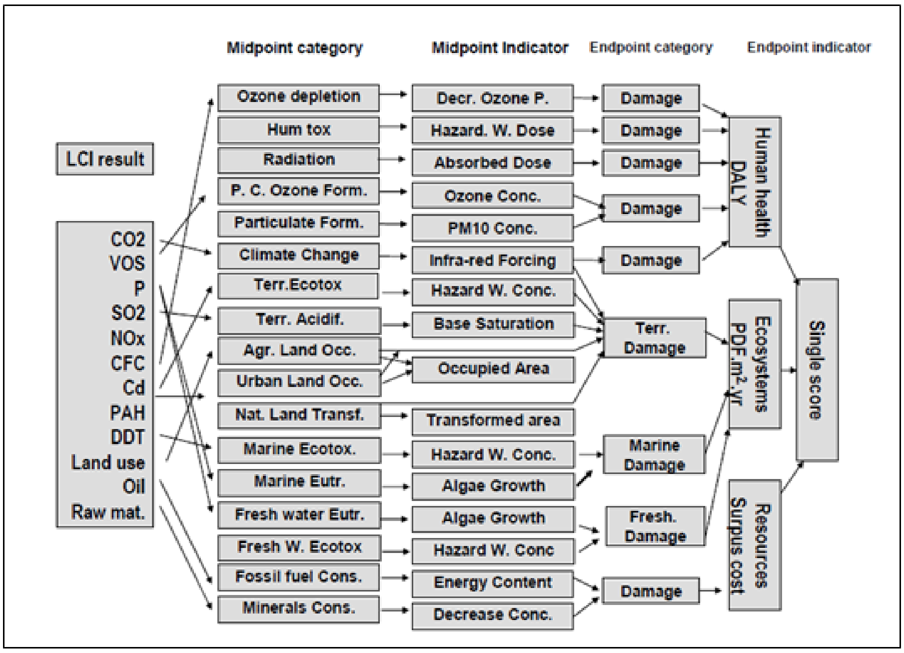


Figure 4.2. Impact categories and pathways covered by the ReCiPe methodology Handbook [2010]

Figure 4.2 shows the widely used ReCiPe methodology which integrates midpoint and endpoint impact categories. All three case studies presented in this chapter used the ReCiPe methodology. ReCiPe was developed to bridge the gap between midpoint and endpoint categories in LCA and provides a consistent framework for evaluating environmental impacts Handbook [2010]. The method offers two levels of assessment:

i. Midpoint indicators: focus on specific environmental processes such as global warming potential and fossil depletion.

ii. Endpoint indicators: assess broader environmental damages, such as impacts on human health or ecosystems

LCA Software Tools

GaBi, SimaPro and OpenLCA are popular software tools for conducting LCAs in the metal industry. These softwares calculate the environmental impacts of products or processes using databases and LCIA methodologies like ReCiPe and CML mentioned earlier.

GaBi (Ganzheitliche Bilanzierung)

GaBi is a versatile tool developed by Sphera, that is widely used across industries for environmental modelling and impact assessment. It supports numerous impact categories and LCIA methodologies and integrates detailed data from various industrial sectors. GaBi is known for its robust datasets and flexibility in handling complex processes.

SimaPro

SimaPro is another leading LCA tool used in research and industry developed by Pre-Sustainability. It supports multiple LCIA methodologies, including ReCiPe and IMPACT 2002+, and provides detailed reporting, scenario analysis, and product comparison functionalities Ciroth et al. [2020].

OpenLCA

OpenLCA is a free, open-source software platform for conducting LCA developed by Green-Delta. It is widely adopted in research and industry for its flexibility and the ability to integrate with databases like Ecoinvent and GaBi. OpenLCA supports numerous LCIA methodologies, including ReCiPe, and is valued for its transparency Ciroth et al. [2020].

Ecoinvent Database

Ecoinvent is a globally recognized LCA inventory database, frequently used in OpenLCA, GaBi and SimaPro. It contains comprehensive environmental data across various sectors, such as energy, transportation, agriculture, and materials. Its comprehensive coverage makes it valuable for conducting LCA in the metal industry. It offers reliable data for assessing resource use, emissions, and other environmental impacts throughout the life cycle of various products and processes.

4.2 Case A: Environmental Assessment of Copper Production in Sweden: A Comparative LCA Approach

This study, done by Sanjuan-Delmás et al. [2022] applies life cycle assessment (LCA) to evaluate the environmental impacts of copper cathode production (99.99% purity) by Boliden Mineral AB in Sweden. Using an open-pit mine and pyrometallurgical refining, the production process, is analysed through a cradle-to-gate LCA, covering the supply chain up to copper cathode production, excluding the product use and end-of-life phases due to variable usage contexts. The assessment relies on two combinations of LCA software and databases for background data: SimaPro with the ecoinvent database and GaBi with the GaBi database. The objective is to analyse differences in environmental performance outcomes based on these software-database pairs and compare findings to similar studies in the literature.

Goals

The study's specific goals were:

i. Creating a comprehensive copper cathode production inventory, encompassing all production stages: mining, beneficiation, and refining.

ii. Assessing the environmental impacts using LCA, comparing results from two setups: SimaPro with ecoinvent, and GaBi with its proprietary database.

iii. Analysing variances between LCA outcomes from the two setups to identify any methodological impact.

iv. Benchmarking these results against similar studies on copper production to place findings in a broader context.

4.2.1 Production Process Overview

The copper cathode production begins at the Aitik open pit mine, where ore extraction, transportation, and initial processing occur, where the key steps are:

i. Mining and Ore Processing: Ore is mined in layers, transported by heavy trucks, and crushed. It is then milled into a fine sand and undergoes flotation, to yield a copper concentrate of 25% Copper Sanjuan-Delmás et al. [2022].

ii. Transport to Smelter: The concentrate is then transported 410 km by train to the smelter in Skelleftea, where it is refined.

The main steps in the pyrometallurgical process are:

i. Drying and Smelting: The concentrate is dried and smelted in a flash unit using oxygen–enriched air. The output is a matte (55–70% Cu) and a slag layer, with gases captured for sulfuric acid production Sanjuan-Delmás et al. [2022].

ii. Converting and Electrolysis: The matte undergoes converting to increase copper purity (97% Cu), with further refining through electrolysis to achieve 99.99% purity Sanjuan-Delmás et al. [2022].

4.2.2 Analysis of Foreground Inventory for Copper Production and Comparison with Literature

The copper production assessment conducted by Boliden Mineral AB provides a detailed inventory for each stage of the process, including mining, concentrator, and smelter operations. Most of the energy consumed is used in the concentrator at Aitik, accounting for 78% of the total electricity demand. In contrast, fossil fuel use is concentrated in the mine, where over 99% of diesel is utilized in mining trucks Sanjuan-Delmás et al. [2022]. Waste rock is the most significant material flow, requiring substantial fossil fuel use for transportation within the mine. Although waste rock has negligible direct environmental impact, its transport–related emissions represent a significant portion of the system's environmental footprint. Other material flows in the mining stage are explosives, lime for water treatment, and generated sludge Sanjuan-Delmás et al. [2022]. The inventory data was compared with similar cases from the literature, highlighting notable differences influenced by factors like ore grade, mining method, and processing type as shown in Table 4.2.

Parameter	(Sweden)	China	China	China	Australia
Ore Grade (% Cu)	0.18	0.81	1.02	0.8	0.1
Mining Type	OP	UM	UM	NS	ISL
Process	P	P	P	HL	ISL
Electricity (MJ)	47,432	15,740	19,330	4,307	10,087
Diesel (MJ)	14,409	11,743	9,657	283	44
Heavy Fuel Oil (MJ)	1,350	9,886	1,869	0	0
Total Energy (MJ)	63,192	39,356	41,311	11,817 (	10,131

Table 4.2. Inventory data Analysis Sanjuan-Delmás et al. [2022]

Where:

i. OP – Open Pit

ii. UM – Underground Mining

iii. P – Pyrometallurgy

iv. HL – Heap Leaching

v. ISL – In-situ Leaching

vi. NS – Not Specified

Sweden Total Energy Analysis

Table 4.2 illustrates that the copper extraction process heavily relies on electricity, particularly for smelting, which accounts for 75% of the total energy consumption as shown in Figure 4.3. Fortunately, many European countries have adopted, or are in the process of adopting, cleaner energy sources, which can mitigate the environmental impact of electricity consumption. However, this is not the case in regions where coal-fired electricity is still regularly used. Diesel makes up 23% of the total energy consumption. Because it is essential for heavy machinery and trucks used in mining, its significant carbon emissions are a major environmental concern. Reducing diesel reliance could substantially lower overall emissions. Heavy fuel oil only contributed 2% to the total energy usage in this case, playing a minor role in the energy profile.

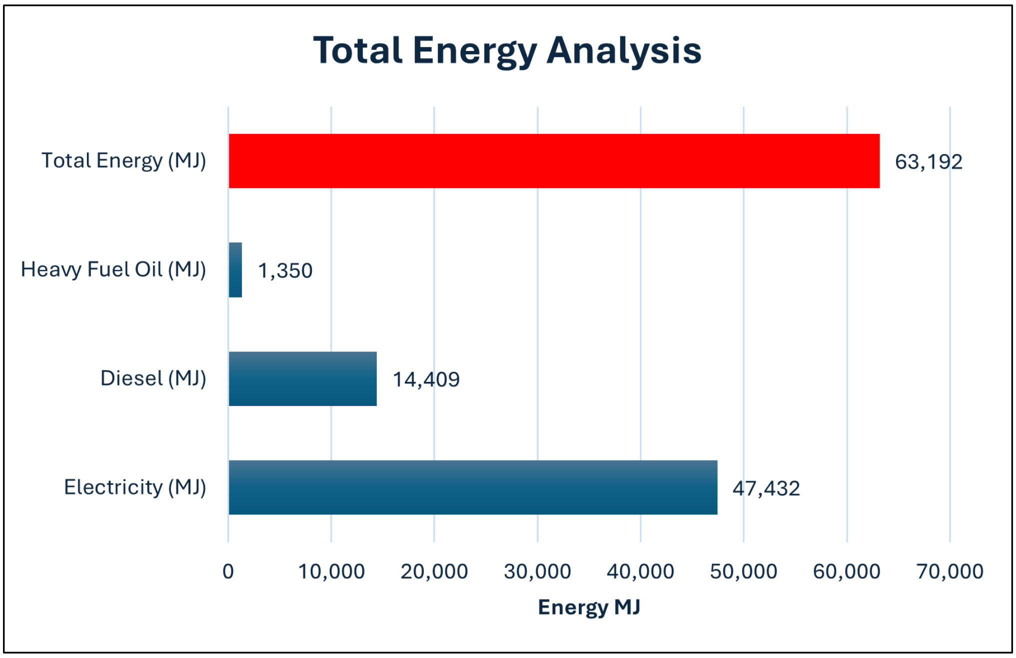


Figure 4.3. Total Energy Analysis Sanjuan-Delmás et al. [2022]

Ore Grade and Total Energy Consumption

Figure 4.4 shows the correlation analysis between ore grade and total energy consumption. The analysis shows a strong negative correlation with an $R^2 = 0.9$. This implies that as the ore grade decreases, the total energy required to process the ore increases. Lower-grade ores require more material to be processed to extract the same amount of copper. The mining method also plays a role, with surface mining requiring more energy than underground mining due to the larger volume of material that must be moved and processed.

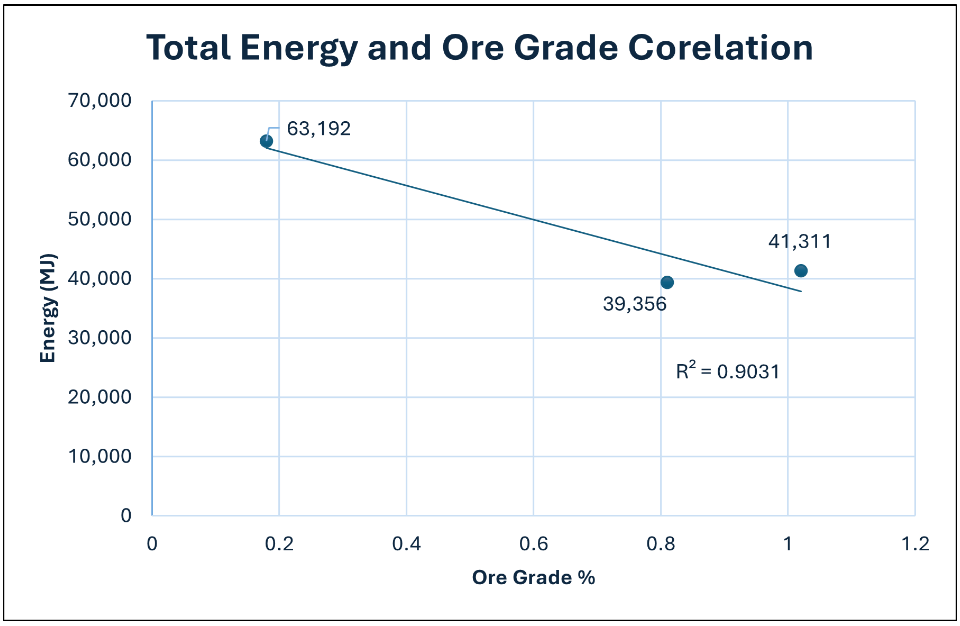


Figure 4.4. Total Energy and Ore Grade Corelation Sanjuan-Delmás et al. [2022]

Electricity Consumption

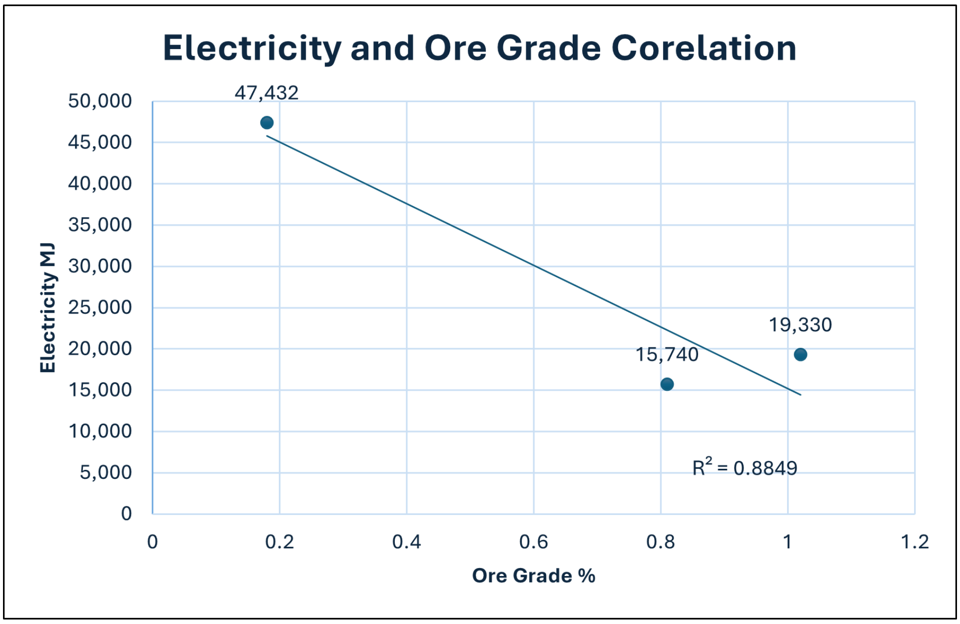


Figure 4.5. Electricity and Ore Grade Corelation Sanjuan-Delmás et al. [2022]

Figure 4.5 shows the correlation between ore grade and electricity consumption, with the highest negative correlation, of $R^2 = 0.95$. This is closely related to the mining method. In surface mining, ore grades are generally lower, Therefore more material needs to be moved, which requires heavy machinery and ultimately more electricity. In underground mining, the ore grades are usually higher, and less material needs to be transported, which results in lower electricity usage. As reported in Table 4.2, the electricity consumption in Sweden for surface mining was 47,432 MJ, compared to 15,740 MJ and 19,330 MJ in the underground mines in China.

Diesel Consumption

Figure 4.6 shows the correlation analysis of diesel consumption which displays a similar trend to the other two figures mentioned earlier. As ore grade decreases, diesel consumption increases, particularly in surface mining operations. This is because surface mining involves transporting more significant amounts of waste material and ore over longer distances. In underground mines, where ore grades are higher and the transport distance is shorter, diesel consumption is significantly lower

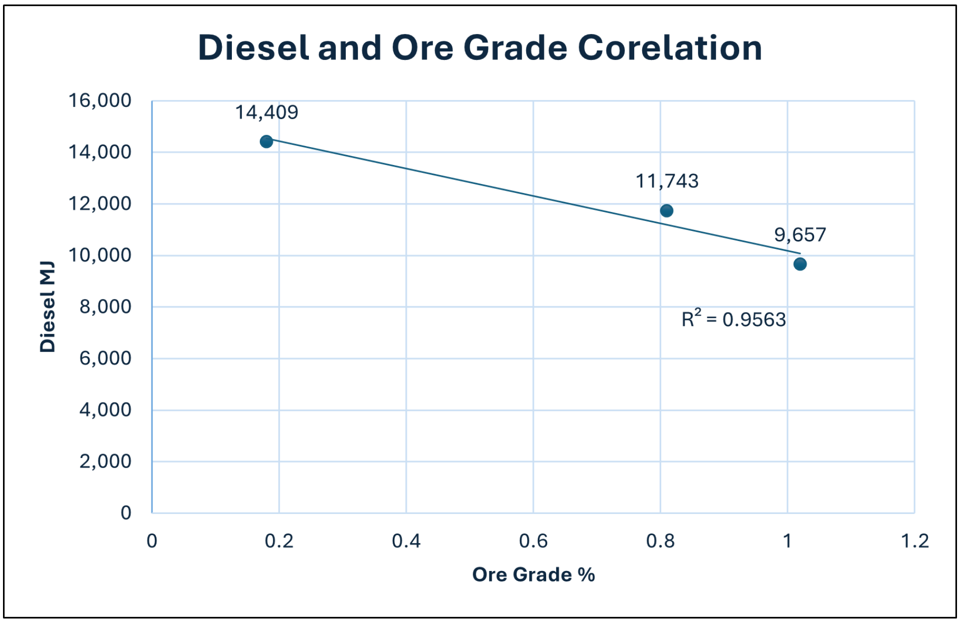


Figure 4.6. Diesel and Ore Grade Corelation Sanjuan-Delmás et al. [2022]

Leaching Methods (ISL)

In-situ leaching (ISL), as observed in the Australian case, requires far less fuel, and the lowest electricity compared to the pyrometallurgy processes thus lowering total energy consumption overall. The diesel required is mostly for transporting acid to the site, and there is minimal movement of materials compared to conventional mining methods. This results in very low diesel usage (44 MJ) and no need for heavy fuel oil. This can benefit, as emissions with lower CO_2 and SO_2 emissions are found in methods that avoid transportation and concentration stages Sanjuan-Delmás et al. [2022].

4.2.3 Environmental Impacts of Copper Production in Sweden

Table 4.3 compares the environmental impacts for producing 1 tonne of copper, using LCA with two different software and database systems: SimaPro with the Ecoinvent database (SS&ED) and GaBi with its own databases (GS&GD). Each impact category shows a variation in results, highlighting differences in how the data is modelled and calculated within each system. Significant variations in results such as Abiotic Depletion, Human Toxicity, and Marine aquatic Ecotoxicity, were observed, with minor differences in Photochemical oxidation, Cumulative

Impact Category	Unit	SS&ED	GS&GD	Ratio(highest/lowest)
Abiotic depletion	kg Sb eq	$1.56E-02$	$2.09E-03$	7.49
Abiotic depletion (fossil fuels)	MJ	$5.13E+04$	$3.99E+04$	1.28
Global warming	kg CO_2 eq	$4.75E+03$	$3.51E+03$	1.35
Human toxicity	kg 1,4-DB eq	$1.54E+03$	$5.52E+02$	2.79
Freshwater aquatic ecotoxicity	kg 1,4–DB eq	$6.98E+01$	$3.45E+01$	2.02
Marine aquatic ecotoxicity	kg 1,4-DB eq	$1.65E+06$	$5.77E+05$	2.85
Terrestrial ecotoxicity	kg 1,4–DB eq	$9.53E+00$	$1.55E+01$	1.63
Photochemical oxidation	kg C_2H_4eq	$1.45E+00$	$1.21E+00$	1.19
Acidification	kg SO_2eq	$3.21E+01$	$2.32E+01$	1.38
Eutrophication	kg PO_4 eq	$3.86E+00$	$2.72E+00$	1.42
Cumulative energy demand	MJ	$1.68E+05$	$1.40E+05$	1.20

Table 4.3. Environmental Impacts of Copper Production in Sweden Sanjuan-Delmás et al. [2022]

The main contributors to environmental impacts across most categories were the transportation of ore within the mine, diesel combustion in trucks, and explosives. According to Sanjuan-Delmás et al. [2022], transportation and explosives accounted for 63–82% of impacts in categories such as Abiotic Depletion (Fossil Fuels), Global Warming, and Eutrophication. Electricity use in the concentrator contributed the most, to Cumulative Energy Demand, although Swedish electricity's reliance on hydropower and nuclear energy minimized Global Warming impacts. Sulphur dioxide emissions from the smelter and mining explosives contributed to impacts of Photochemical Ozone Formation and Acidification.

4.2.4 Comparisons of Environmental Impacts of Copper Production

Table 4.4 compares the Global Warming (GW) and Cumulative Energy Demand (CED) for 1 Tonne of Copper Production Across Various Studies.

Authors, Year	Country	Ore Grade (% Cu)	Mining Type	Process	GW (kg CO2 eq)	CED (MJ)
Norgate et al. (2007)	Australia	2.00	NS	H	6200	64,000
Moreno-Leiva et al. (2017)	Chile	0.71	NS	P	6000	NS
Moreno-Leiva et al. (2017)	Chile	0.71	NS	H	4900	NS
Haque & Norgate (2014)	Australia	0.10	ISL	IsL	4780	61,000
Sweden – S&E	Sweden	0.18	OP	P	4750	168,000
Sweden – GaBi	Sweden	0.18	OP	P	3510	140,000
Norgate et al. (2007)	Australia	3.00	NS	P	3300	33,000
Hong et al. (2018)	China	1.02	NS	H	1910	NS
Ecoinvent	Europe	–	–	–	1637	29,811

Table 4.4. Comparison of Global Warming (GW) and Cumulative Energy Demand (CED) for 1 Tonne of Copper Production Across Various Studies Sanjuan-Delmás et al. [2022]

Comparison of Global Warming (GW) for copper Production

Figure 4.7 compares the global warming potential across multiple studies, providing insights into the environmental impacts of producing 1 tonne of copper under different mining conditions, processes, and ore grades.

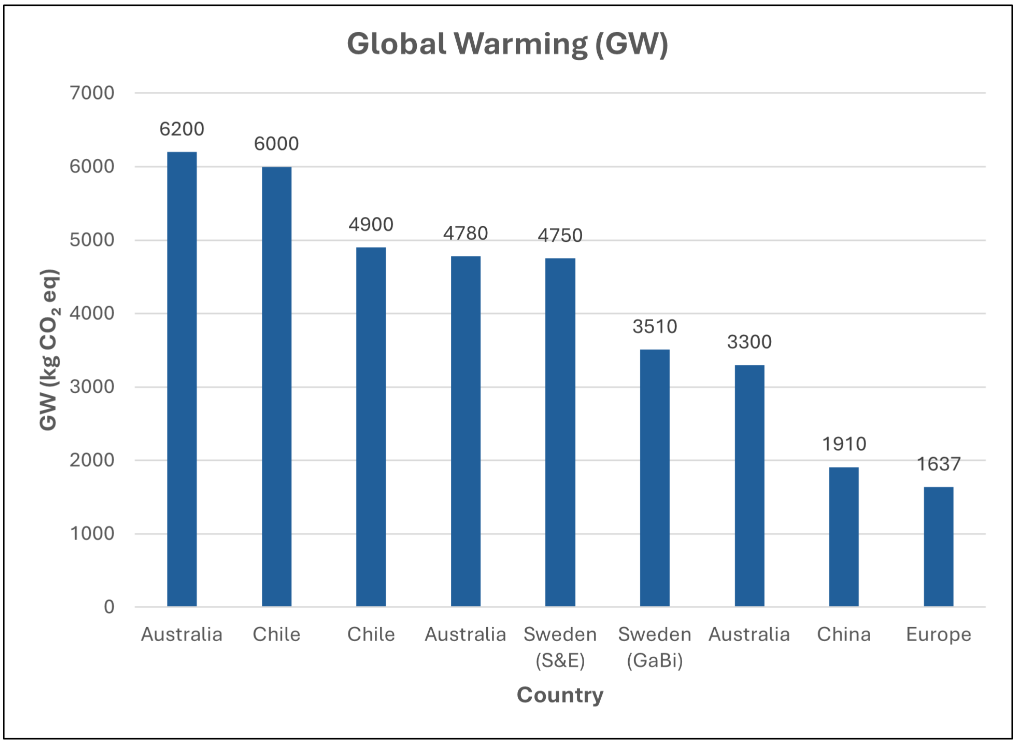


Figure 4.7. Comparison of Global Warming for copper Production Sanjuan-Delmás et al. [2022]

The global warming potential expressed in kg CO_2 eq, varies significantly across different studies, reflecting differences in ore grade, mining type, and copper production processes:

i. Norgate et al. (2007) reports the highest GW of 6200 kg CO_2 eq for hydrometallurgical copper production in Australia with a high ore grade of 2%. The high GW impact in this case may be attributed to the energy-intensive extraction processes and regional energy sources, possibly fossil fuels Sanjuan-Delmás et al. [2022].

ii. The S&E, conducted in Sweden, reports a GW potential of 4750 kg CO_2 eq for copper production from low-grade ore of 0.18% using open-pit mining and pyrometallurgical processing. The combination of low-grade ore and energy-intensive pyrometallurgy significantly contributes to the overall emissions.

iii. The GaBi data for this case study presents a lower GW value of 3510 kg CO_2 eq, showing some variation in results depending on the life cycle assessment (LCA) software used.

iv. The Ecoinvent dataset used in Europe showed the lowest GW impact of (1637 kg CO_2 eq), because of the use of cleaner energy sources and efficient production processes in Europe. Although specific mining and processing details are not provided, this suggests regional energy efficiency and technology adoption differences.

Cumulative Energy Demand (CED) for Copper Production

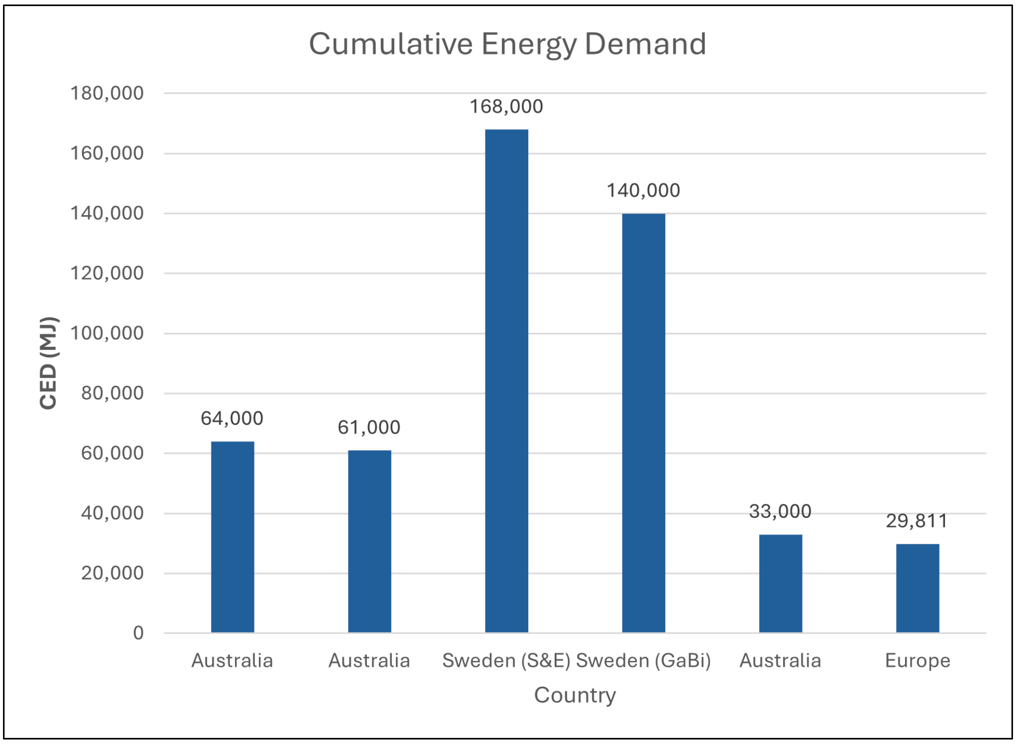


Figure 4.8. Cumulative Energy Demand (CED) for Copper Production Sanjuan-Delmás et al. [2022]

Figure 4.8 shows the cumulative energy demand; it also highlights significant variation between high and low-grade ore deposits:

i. S&E reports the highest CED of 168,000 MJ for copper production from low-grade ore using pyrometallurgical processing. The high energy requirement reflects the increased energy intensity associated with processing larger volumes of ore to extract copper at such low concentrations.

ii. GaBi results for this case study show a lower CED of 140,000 MJ, again highlighting the influence of different LCA methodologies. Even so, these results still represent high energy demand due to the low ore grade and the energy-intensive nature of pyrometallurgy.

iii. Norgate et al. (2007) report much lower CED values for higher-grade ores for example, 33,000 MJ for a 3% ore grade in Australia. This highlights the correlation mentioned earlier, between ore grade and energy demand, with higher ore grades requiring less energy per tonne of copper produced.

iv. Ecoinvent dataset in Europe presents a relatively low CED of 29,811 MJ, suggesting that copper production in Europe is more energy-efficient, possibly due to cleaner energy sources and modern production technologies.

Principal Findings

Ore Grade Impact

The results show a clear correlation between ore grade and GW and CED. Lower ore grades require significantly more energy and lead to higher greenhouse gas emissions due to the larger quantities of ore that must be processed. This is particularly evident in the comparisons of this case study with other cases with higher ore grades.

Process Type

The production process plays a crucial role in determining the environmental impact. Hydrometallurgical processes, generally result in lower GW and CED values than pyrometallurgical processes, due to reduced energy requirements.

LCA Software and Regional Differences

The differences between SimaPro and GaBi results in this study highlight the importance of LCA software selection. Moreover, the Ecoinvent data demonstrates that copper production in Europe is less energy-intensive, due to a higher reliance on renewable energy and more efficient industrial processes.

4.2.5 Conclusion for Case A

This study emphasises the importance of choosing the appropriate LCA tool and database when assessing the environmental impacts of copper production. The results also highlight how ore grade and mining methods influence energy consumption and environmental impacts. Swedish copper production benefits from low-carbon electricity sources, reducing its global warming potential despite energy-intensive processes like smelting. Comparisons with studies from other regions show that lower-grade ores and surface mining are more energy-demanding, though technologies like in-situ leaching could significantly lower environmental burdens.

4.3 Case B: Environmental Analysis of Reprocessing Sulfidic Tailings in Portugal

This case study presents a process-based LCA to evaluate the environmental impacts of various reprocessing routes for sulfidic mine tailings at a site in Portugal. The current practice involves the generation of tailings from metal ore beneficiation, with deposition in tailings management facilities. This LCA explores alternative reprocessing routes, focusing on different technologies to recover metals and valorise the tailings, comparing these options to the baseline scenario of direct landfilling without treatment. The functional units for this analysis include the disposal of 1 tonne (t) of sulfidic tailings, as well as the production of materials and by-products through various reprocessing routes Adrianto and Pfister [2022]. The outputs were:

i. 1.56 t of calcium sulfo-aluminate (CSA) cement

ii. 4.1 t of ceramics

iii. 0.69 t of geopolymer (equivalent to Portland cement)

iv. 2.9 kg of copper and 7.5 kg of zinc

v. 110 kg of sulfuric acid

vi. 182 MJ of heat energy

A zero-burden approach is assumed, which excludes the environmental impacts from the previous life cycle stages before the waste generation. A system expansion approach gives credit for reducing the need to produce metals, building materials, and by-products through primary production. This is because reprocessing of tailings provides these materials, saving resources that would otherwise have to be extracted. The impacts of use and end-of-life phases were excluded due to insufficient data, and the substitution ratios for secondary products are explored through sensitivity analysis.

4.3.1 Tailings Reprocessing Routes

Adrianto and Pfister [2022] developed four reprocessing routes, for copper tailings based on inputs from the SULTAN project and literature sources. These are categorized as Route A (with sub-routes A1 and A2) and Route B (with sub-routes B1 and B2). While Route A focuses on separating sulphur-rich fractions for calcium sulfo-aluminate (CSA) cement production and aluminosilicates for ceramic and geopolymer production, Route B emphasizes metal recovery before valorising the remaining aluminosilicate materials.

Route A: Flocculation-Flotation Process

In Route A, a flocculation-flotation process is applied to separate sulphur-rich fractions from aluminosilicate fractions in the tailings. This method, adapted from (Broadhurst et al.2015), uses polyacrylamide and xanthate as flocculants and collectors to enhance pyrite separation from the aluminosilicates.

i. Sulphur-Rich Fraction: This fraction is directed toward CSA cement production, offering an alternative to conventional cement and reducing the need for primary resources.

ii. Aluminosilicate Fraction: Depending on the sub-route, the aluminosilicate-rich fraction is vaporized as follows:

a. Route A1: The fraction is used in ceramic roof tile production.

b. Route A2: The fraction is used in geopolymer production.

Environmental Benefits of Route A

Route A contributes to reducing landfill use and promoting sustainable construction materials by displacing primary resources in CSA cement, ceramics, and geopolymers. Substituting primary building materials reduces environmental impacts, including CO_2 emissions and resource depletion.

Route B: Metal Recovery with Microwave Roasting and Leaching

Route B combines pyrometallurgical and hydrometallurgical techniques to recover copper and zinc before valorising the residual aluminosilicates.

Microwave Roasting

Tailings are first homogenized, dried, and then subjected to microwave roasting. This step facilitates pyrite oxidation between between 380°C and 730°C, releasing sulphur off-gases for subsequent sulfuric acid production.

Ammoniacal Leaching

Roasted tailings are leached using ammonia and ammonium carbonate solutions, which dissolve copper and zinc into a pregnant leach solution (PLS) Adrianto and Pfister [2022]

Metal Recovery

a. Copper is recovered from the PLS through ion flotation.

b. Zinc is precipitated from the aqueous phase.

Residue Valorisation

After metal recovery, the aluminosilicate residues are valorised into:

a. Route B1: Ceramic roof tiles production.

b. Route B2: Geopolymers production.

Environmental Benefits of Route B

Route B offers multiple environmental credits by avoiding tailings landfill, displacing primary metals (2.9 kg of copper and 7.5 kg of zinc), and producing sulfuric acid (110 kg) and heat (182 MJ) from the off-gases. These by-products, which would otherwise require additional resource inputs, further contribute to the process's sustainability. Table 4.6 summarise all the routes that were described.

Process Step	Route A1 (%)	Route A2 (%)	Route B1 (%)	Route B2 (%)
Beneficiation	Flocculation–flotation	Flocculation–flotation	MW–roasting and leaching	MW–roasting and leaching
Recovery	–	–	Ion flotation and precipitation	Ion flotation and precipitation
Residue	CSA cement production	CSA cement production	–	–
Valorisation	Ceramic roof tile production	Geopolymer production	Ceramic roof tile production	Geopolymer production
Displaced Metals	–	–	2.9 kg copper, 7.5 kg zinc	2.9 kg copper, 7.5 kg zinc
Displaced Building Materials	1.56 t CSA cement, 4.1 t ceramic tiles	1.56 t CSA cement, 0.69 t Portland cement	3.4 t ceramic tiles	0.58 t Portland cement
Other By-products	–	–	110 kg sulfuric acid, 182 MJ heat	110 kg sulfuric acid, 182 MJ heat

Table 4.5. Overview of Tailings Reprocessing Routes Adrianto and Pfister [2022]

4.3.2 Life Cycle Impact Assessment and Inventory Analysis

Adrianto and Pfister [2022] performed this study using mid and endpoint indicators from the ReCiPe method, supplemented by cumulative energy demand (CED) and toxicity-related indicators from USEtox. This provided a comprehensive overview of the environmental impacts associated with waste management and resource recovery. The life cycle inventory data were primarily sourced from in-house experiments conducted by the SULTAN project (2018), which were scaled to commercial levels using ex-ante LCA frameworks. Secondary sources were used to fill data gaps when experimental data were unavailable. Following a hierarchical approach, well-documented data were prioritized, while expert judgments and insights from process developers helped determine equipment and process parameters when needed. Where further data gaps remained, engineering-based calculations Piccinno et al. [2016] and proxy data from similar large-scale applications were applied. This comprehensive approach ensured accuracy in the technology-specific inventory calculations.

4.3.3 Results

Figure 4.9 compares the environmental impacts in terms of CO_2 equivalent (eq) emissions of processes that use primary resources with substituted processes that produce valorised products. The results highlight the better environmental performance of the valorised products across all three processes; ceramic tile production, CSA cement production, and geopolymer production.

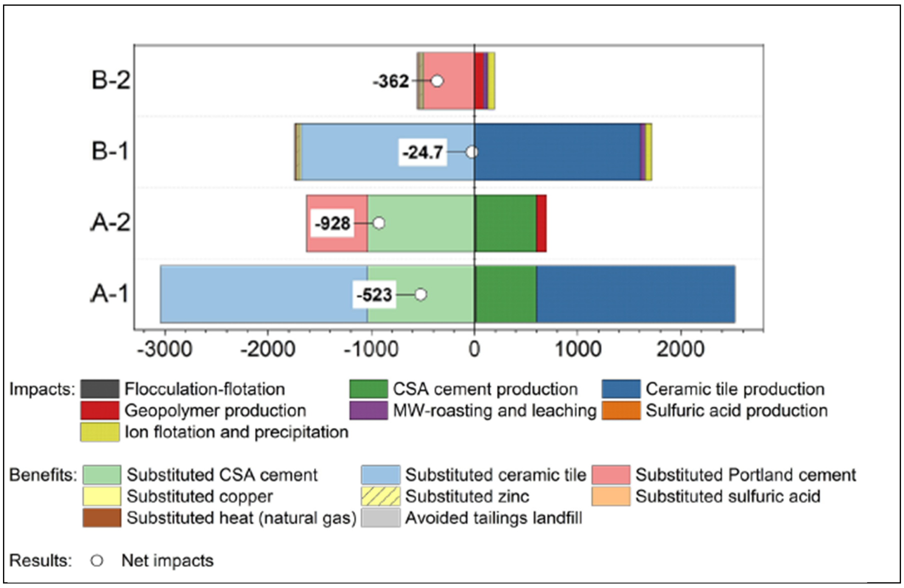


Figure 4.9. Climate Change impacts (kg CO_2-equivalent) Adrianto and Pfister [2022]

i. **Ceramic Production:**

Using primary resources has a relatively high environmental impact, but its substituted process of using valorised products slightly reduces this impact. The substituted ceramic production shows a net benefit of –24.7 kg CO_2 eq. This represents a small environmental gain, because the overall benefit is limited by the fact that 1 tonne of tailings is used to produce 3 to 4 tonnes of ceramics and this increases energy consumption and processing burdens, eventually reducing the net environmental savings.

ii. **CSA Cement Production:**

CSA cement production has a favourable net environmental impact. For every tonne of tailings processed, 1.56 tonnes of CSA cement are produced, resulting in a significant net environmental benefit of –928 kg CO_2 eq in A2 route as shown in Figure 4.9. This shows that CSA cement valorisation effectively displaces primary cement production with significant environmental savings.

iii. **Geopolymer Production:**

In B2 route, the geopolymer production results in a positive environmental performance. Producing geopolymers generates a benefit of the net impact of –362 kg CO_2 eq, as opposed to Portland cement production as shown in Figure 4.9. Although the production volume is lower (0.6 to 0.7 tonnes per tonne of tailings), the net environmental savings are still substantial.

Ecotoxicity

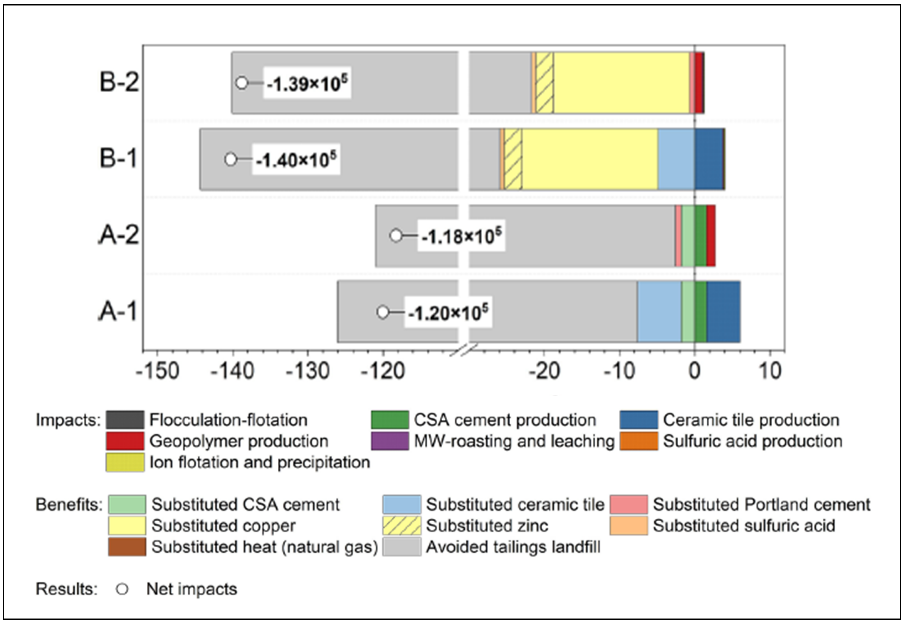


Figure 4.10. Ecotoxicity (1000 CTUe) Adrianto and Pfister [2022]

Figure 4.10 illustrates the ecotoxicity impacts of the core and substituted processes. The differences between them are relatively minor, with the substituted ceramic production showing a slightly higher impact than the core ceramic production. Similarly, for CSA cement and geopolymer production, the ecotoxicity impacts of the substituted and core processes are almost the same. However, when the "Avoided tailings landfill" benefit is factored in, the substituted processes offer significantly better environmental performance. The benefit of avoiding tailings disposal in landfills greatly outweighs the minor differences in ecotoxicity between the core and substituted processes. As shown in Table 4.6, the avoided landfill benefits, significantly reduce the ecotoxicity impact of the substituted routes:

Route	Avoided Tailings Landfill ($10^3 CTUe$)
A1	–1,2 x 10^5
A2	–1,18 x 10^5
B1	–1,4 x 10^5
B2	–1,39 x 10^5

Table 4.6. Overview of Tailings Reprocessing Routes Adrianto and Pfister [2022]

The notable reductions in ecotoxicity are primarily attributed to the recovery of copper and zinc in Routes B. As a result, the values for sub-routes B1 and B2 are slightly higher than those for sub-routes A1 and A2, which do not involve metal recovery. This underscores the importance of incorporating metal recovery into the valorisation processes to reduce the risk of groundwater contamination by preventing heavy metal leaching from tailings.

Cumulative Energy Demand (CED)

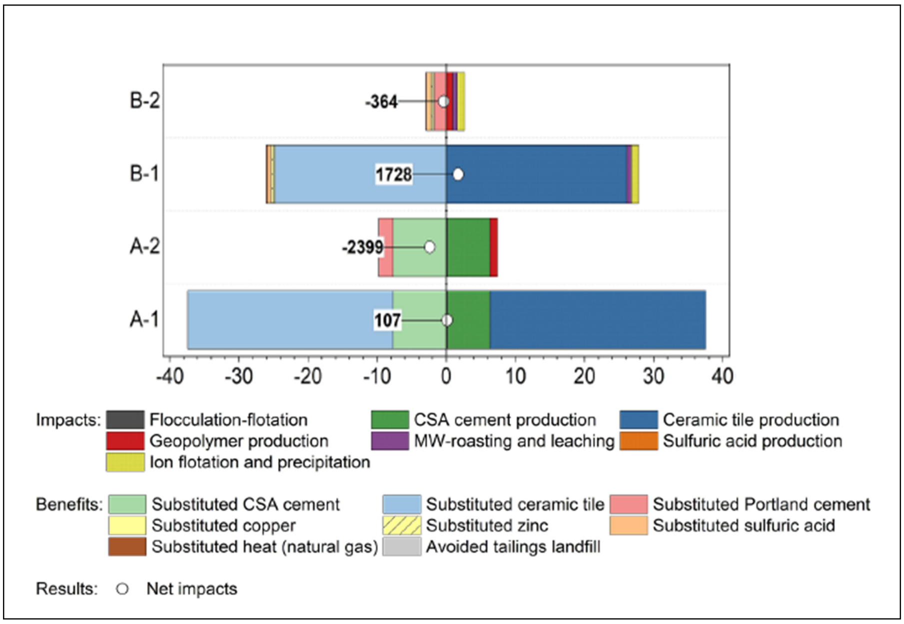


Figure 4.11. CED (1000 MJ –equivalent) Adrianto and Pfister [2022]

Figure 4.11 highlights the difference in Cumulative Energy Demand (CED) between core and substituted processes for various products, including the net energy savings or impacts for each. CED measures the total energy required across a process's life cycle, expressed in megajoules (MJ).

i. Ceramics Production

For ceramic tile production, the difference between the core process demands and the substituted ceramic production process is 1728 MJ as shown in Figure 4.11. Although the substituted process does offer some energy savings, the change is not significant. This indicates that ceramics production is energy-intensive regardless of the process used.

ii. CSA and Geopolymer

CSA cement production benefits greatly from the substituted process. The difference between the core process and the substituted method has a net energy savings of -2399 MJ as shown in Figure 4.11. This demonstrates a substantial energy advantage when using the substituted method for CSA cement production. Likewise, for geopolymer production, there is a net energy savings of -364 MJ when the substituted method is used. This further highlights the significant energy benefits of the substituted processes for CSA cement and geopolymer production.

Figure 4.11 shows that roasting and leaching for metal recovery require energy inputs, amounting to 107 MJ, contributing to the overall energy demand in routes involving metal recovery.

Particulate Matter Formation Potential (PMFP)

Particulate Matter Formation Potential (PMFP) quantifies the potential emissions of particulate matter, expressed in terms of PM10-equivalents. PM10 refers to particulate matter with a diameter of 10 micrometres or less, which can be inhaled and cause adverse health effects. The PMFP metric is essential for evaluating the environmental impacts of production processes, as it provides an understanding of how much particulate matter can be generated during the lifecycle of a product.

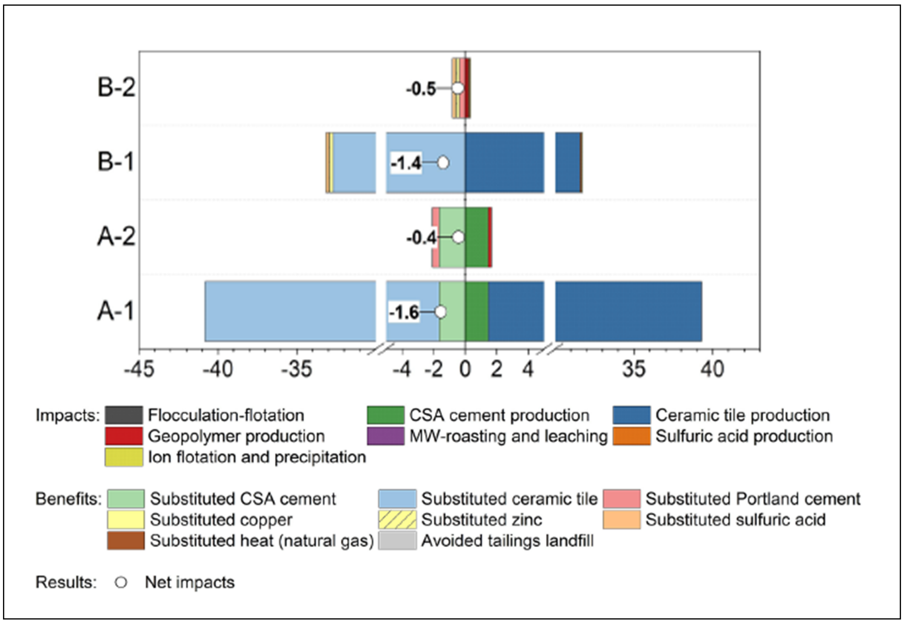


Figure 4.12. PMFP (kg PM 10-equivalent) Adrianto and Pfister [2022]

The analysis in Figure 4.12 shows negative values for substituted processes, this highlights the environmental benefits of valorising materials through alternative processes that result in lower PMFP compared to traditional production methods, although the differences in PMFP values are relatively low.

4.3.4 Sensitivity Analysis of Tailings Reprocessing Routes

The sensitivity analysis on the four reprocessing routes for copper tailings reveals critical insights into their environmental performance, emphasizing the importance of process parameters, transport distances, energy sources, and product quality.

Performance Against Primary Production Routes

The analysis shows that most evaluated routes perform below the environmental impacts associated with primary production, with 28 out of 32 indicators demonstrating this trend. Applying best-case assumptions improved performance across all indicators, particularly in categories such as climate change, cumulative energy demand, and fossil depletion potential as shown in Figure 4.13. However, the metal-only recovery methods did not reach breakeven points for low-grade tailings, indicating limitations in their effectiveness. The whiskers indicate best cases (lower range) and worst cases (higher range). For worst cases, red dots indicate values that exceed the 100% threshold.

Routes A-1 and B-1: Impact and Energy Consumption

Figure 4.13 Routes focused on maximizing ceramic production outputs (A-1 and B-1) showed higher environmental impacts than virgin production in the CC, FDP, and CED categories. This increase can be attributed to elevated thermal energy and electricity consumption during manufacturing. Additionally, particulate emissions significantly influenced the PMFP and ReCiPe (H) endpoint indicators. Implementing effective dust and particulate abatement technologies could potentially enhance environmental performance in these routes.

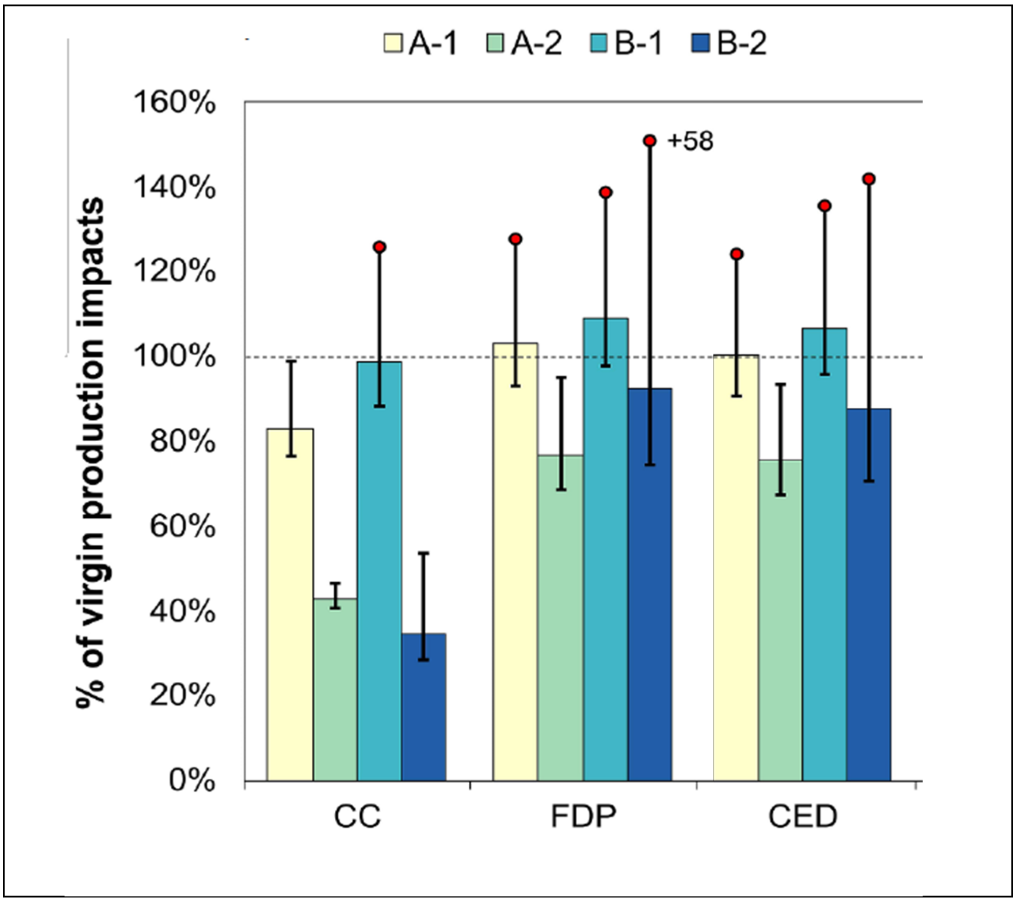


Figure 4.13. Comparison of Impacts; CC, FDP, CED Adrianto and Pfister [2022]

Metals Recovery: Routes B-1 and B-2

Routes incorporating metals recovery (B-1 and B-2) revealed moderate gains in materials demand potential (MDP), human toxicity, and freshwater ecotoxicity, maintaining less than 30% of the impacts of virgin production, even under worst-case scenarios as shown in Figure 4.14. The variability in impact results highlights the sensitivity of these routes to the use of emerging technologies in the inventory models. For example, Route

B2, incorporates advanced processes with high uncertainties such as microwave roasting, leaching, ion flotation, and geopolymer production. This is because these technologies are still in the early stages of development, leading to a lack of established data and increased variability in performance outcomes. As a result, the environmental impacts of these processes are more difficult to predict accurately.

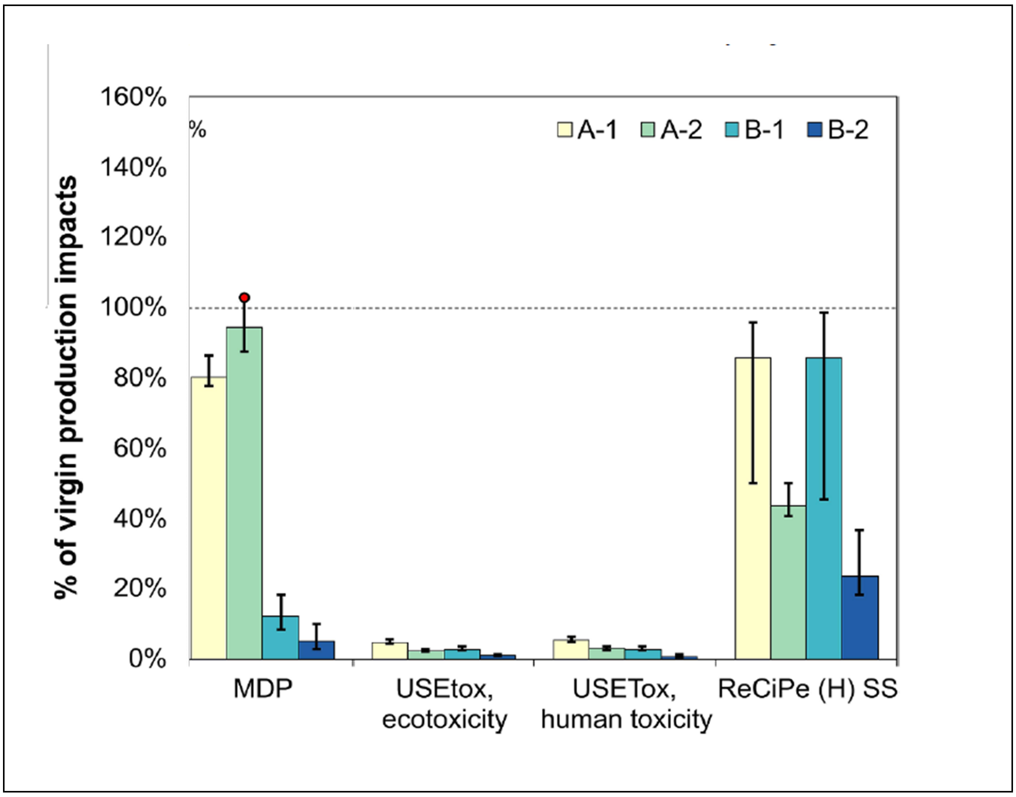


Figure 4.14. Comparison of Impacts; MDP, ecotoxicity, ReCipe Adrianto and Pfister [2022]

Transport Distance Sensitivity

The sensitivity analysis regarding transport distances indicates that delivery by truck contributes a low to moderate increase in overall environmental impacts, primarily resulting from the bulk transfer of raw tailings. Specifically, a 50 km transport distance was found to contribute less than 2% to overall impacts, while longer transport distances such as 300 km resulted in a 4 to 5% increase in specific indicators such as CED, CC, and toxicity-related categories Adrianto and Pfister [2022].

Energy Transitions

Transitioning to a decarbonized electricity supply is projected to improve the life cycle performance of all reprocessing routes, with an expected 11% decrease in impacts from the base case by 2030. However, this transition also poses a trade-off: MDP and ecotoxicity indicators may show different trends due to increased metal requirements for low-carbon power generation (e.g., solar and wind), which can lead to emissions from associated metal mining Adrianto and Pfister [2022].

Impact of Product Quality on Substitution Ratios

The analysis reveals that secondary products of inferior quality negatively affect substitution ratios, resulting in worse environmental performances than base cases. An average increase of 14% across all indicators and routes highlights the significance of product quality in determining the sustainability outcomes of tailings valorisation.

4.3.5 Conclusion for Case B

The results offer valuable insights into emerging processes' environmental performance and highlight key improvement areas. The prospective LCA approach was critical in pinpointing elements within the process chains that need optimization to make these routes more sustainable. Mineral valorisation processes were found to significantly impact categories such as climate change (CC), cumulative energy demand (CED), and particulate matter formation potential (PMFP). Metal recovery processes showed substantial environmental benefits, particularly in metal depletion and toxicity reduction. The concentration of metals in the tailings plays a crucial role in the success of metal recovery routes, with higher metal concentrations leading to more favourable environmental outcomes.

4.4 Case Comparisons

4.4.1 Environmental Impacts

Table 4.7 compares the environmental impacts of two case studies: Case B, which focuses on the valorisation of copper tailings using four different reprocessing routes, and Case A, which examines copper production in Sweden. The results shows that Case B generally provides positive environmental effects, with many impact categories having negative values, indicating environmental benefits. In contrast, Case A shows high positive values in most categories, reflecting higher environmental burdens. Seven impact categories with the most significant differences between the two cases are further examined separately.

Impact Category	Unit	SS&ED	GS&GD	Route A1	Route A2	Route B1	Route B2
Abiotic depletion	kg Sb eq	0.016	0.0021	-9.60	-1.40	-136.27	-129.47
Abiotic depletion (fossil fuels)	MJ	51300	39900	29.05	-52.35	62.26	-5.70
Global warming	kg CO_2 eq	4750	3510	-523.18	-927.61	-24.68	-362.37
Human toxicity	kg 1,4-DB eq	1540	552	-2670.10	-2571.47	-3006.00	-2923.64
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	69.8	34.5	-239.61	-232.42	-309.92	-303.91
Marine aquatic ecotoxicity	kg 1,4-DB eq	1650000	577000	-203.16	-198.07	-264.39	-260.14
Terrestrial ecotoxicity	kg 1,4–DB eq	9.53	15.5	-0.048	-0.008	0.316	0.349
Photochemical oxidation	kg C_2H_4eq	1.45	1.21	-0.93	-1.05	-0.76	-0.87
Acidification	kg SO_2eq	32.1	23.2	-0.53	-0.94	-0.83	-1.17
Eutrophication	kg PO_4 eq	3.86	2.72	-0.36	-0.05	-0.58	-0.32
Cumulative energy demand	MJ	168000	140000	106.93	-2398.67	1727.67	-364.33

Table 4.7. Comparison of Environmental Midpoint Impacts for Case Study A and B

Mineral Depletion Potential (MDP)

Figure 4.15 shows that Case B's Mineral Depletion Potential (MDP) is significantly lower than Case A's, especially in Routes B1 and B2, which show large negative values (-136.27and -129.47 kg Sb eq). This indicates substantial environmental credits due to the recovery of residual minerals from tailings in these routes. By reprocessing the tailings, these routes reduce the demand for extracting primary minerals, which helps conserve natural resources.

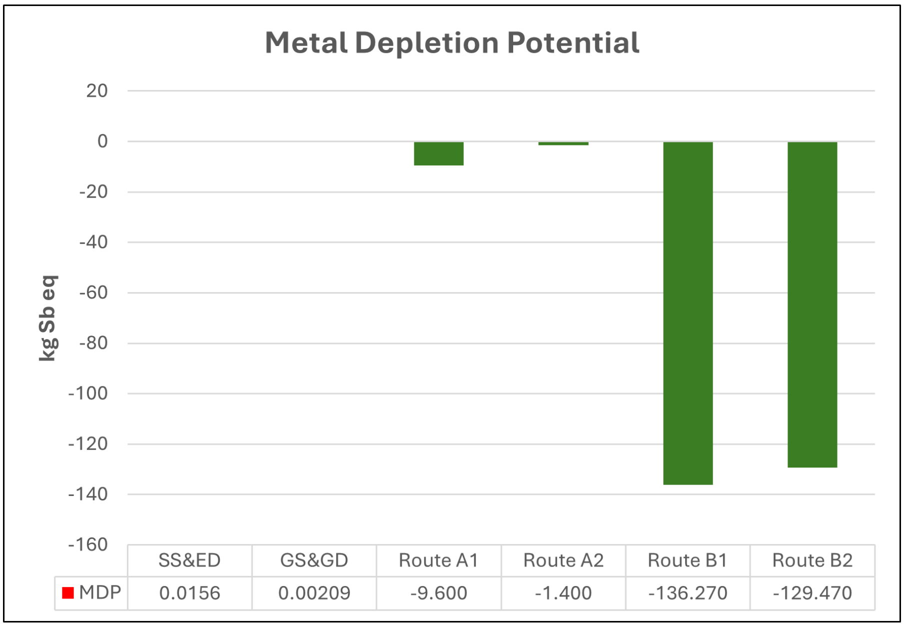


Figure 4.15. Mineral Depletion Potential (MDP

Fossil Depletion Potential (FDP)

Case A in Figure 4.16 again show a much higher value for abiotic depletion of fossil fuels due to the large amounts of diesel used in ore and waste transportation during copper mining. In comparison, valorisation routes in Case B generally have negative values, indicating that tailings reprocessing, at or near mining sites, can save fossil fuel resources, contributing positively to the environment

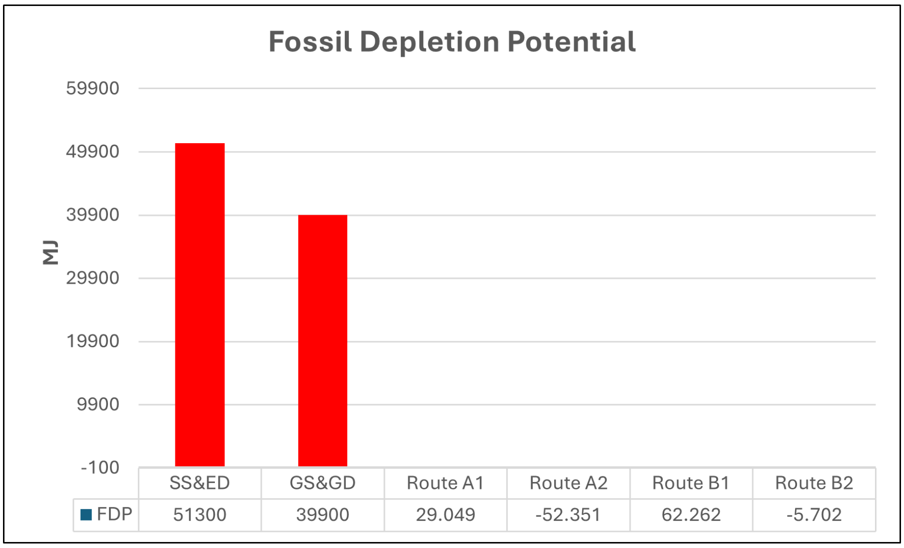


Figure 4.16. Fossil Depletion Potential (FDP)

Global Warming Potential (GWP)

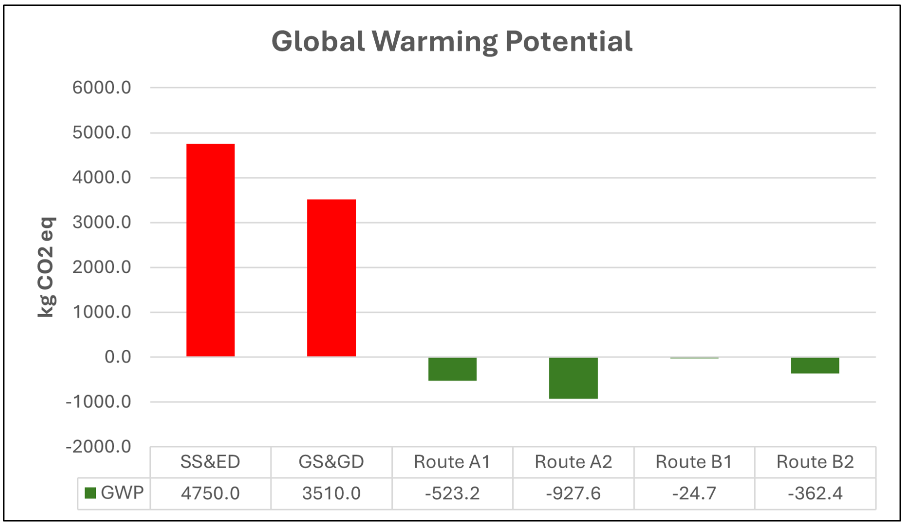
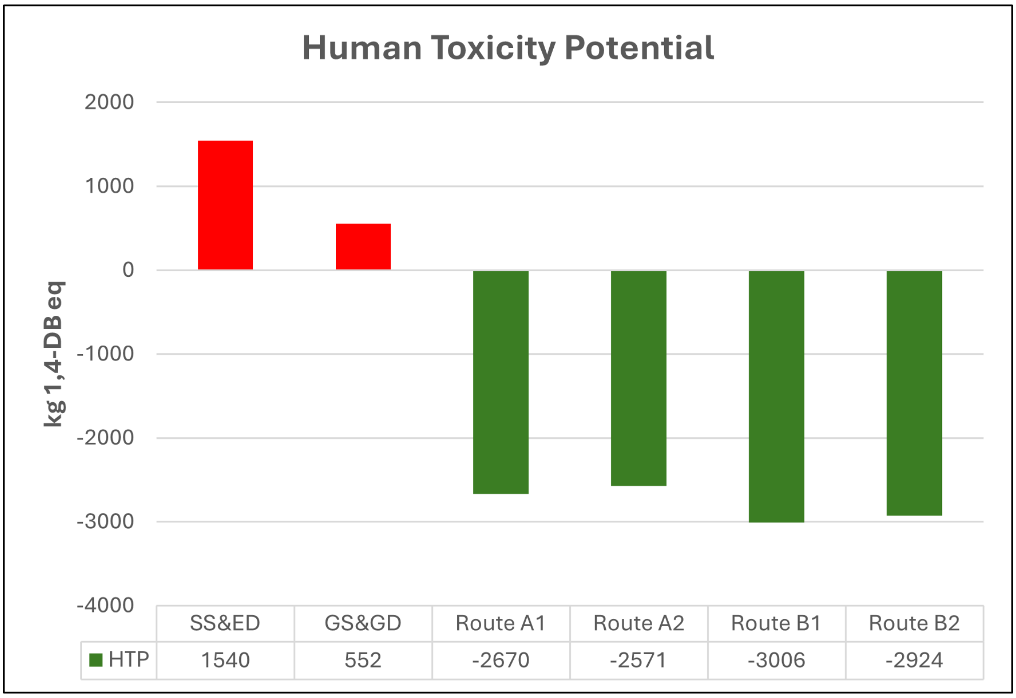


Figure 4.17. Global Warming Potential (GWP)

Figure 4.17 Reflects the trend observed with fossil depletion. The primary copper production in Case A shows high GWP values due to the energy-intensive nature of the extraction process, leading to significant CO_2 emissions. In contrast, all four valorisation routes in Case B show negative GWP values, with Route A2 offering the greatest environmental benefit at -927.612 kg CO_2 eq. These negative values demonstrate that reprocessing tailings reduces the need for primary resource extraction and mitigates the overall impact on climate change

Human Toxicity Potential (HTP)

The Human Toxicity Potential (HTP) is another area where significant differences are observed as shown in Figure 4.18. Copper production in Case A shows a much higher potential for human health risks due to releasing of toxic substances throughout the mining and refining processes. However, in Case B, all valorisation routes exhibit large negative values, with Route B1 achieving -3006 kg 1,4-DB eq. This suggests that reprocessing tailings not only prevents the release of harmful substances but also contributes positively by reducing overall human toxicity risks.



	SS&ED	GS&GD	Route A1	Route A2	Route B1	Route B2
🟩 HTP	1540	552	-2670	-2571	-3006	-2924

Figure 4.18. Human Toxicity Potential (HTP)

Human Toxicity Potential

Figure 4.19 shows that freshwater ecosystems are susceptible to contamination from copper mining operations, as shown in Case A. In contrast, the valorisation processes in Case B provide significant environmental credits, with Routes B1 and B2 showing an average value of around -300 kg 1,4-DB. These negative values highlight the environmental benefits of tailings reprocessing, as it significantly reduces freshwater contamination compared to traditional mining operations.

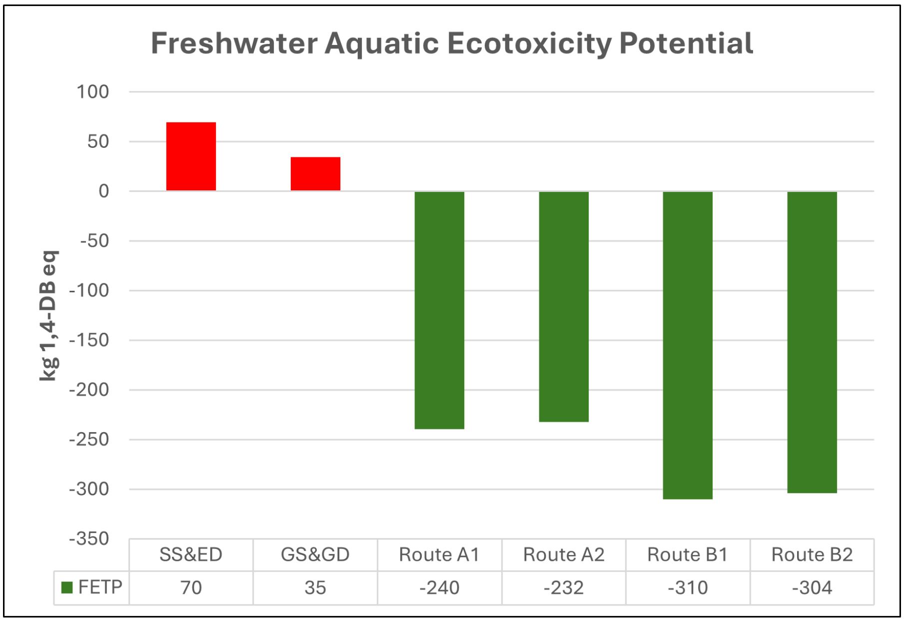


Figure 4.19. Freshwater aquatic ecotoxicity

Marine Aquatic Ecotoxicity Potential (METP)

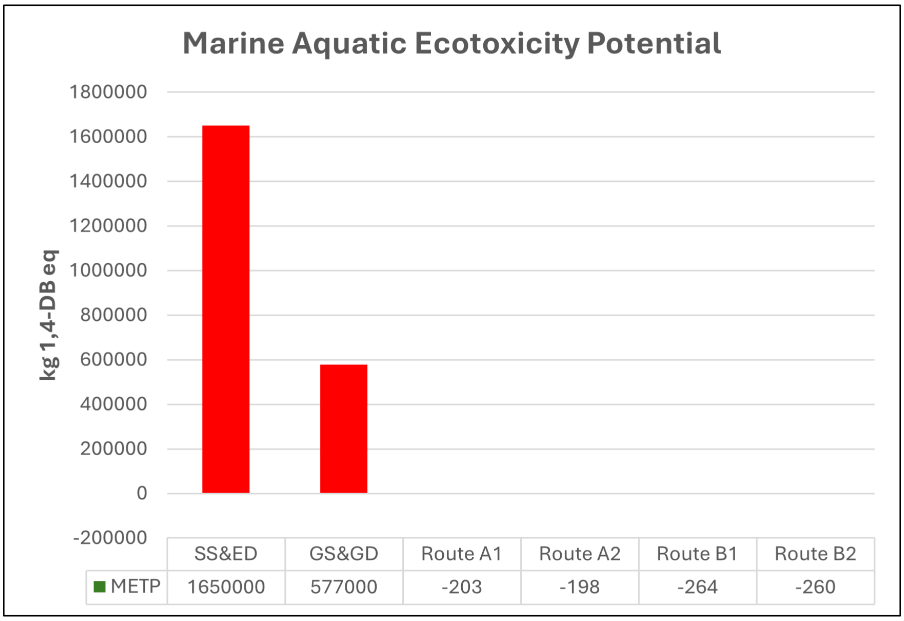
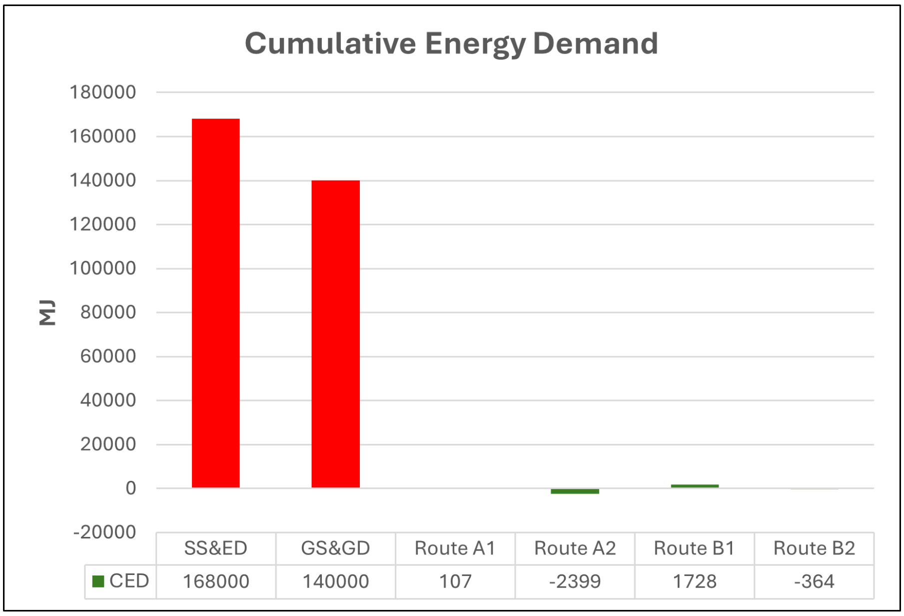


Figure 4.20. Marine Aquatic Ecotoxicity Potential (METP)

Figure 4.20 highlights that the marine aquatic ecotoxicity potential has a similar trend as fossil depletion, with copper production in Case A contributes much more to marine pollution than the valorisation routes in Case B. Routes B1 and B2 demonstrate the most significant reductions, with values around -260 kg 1,4-DB eq., suggesting that valorisation processes reduce the harmful effects on marine life, which are otherwise worsened by conventional copper mining.

Marine Aquatic Ecotoxicity Potential (CED)



	SS&ED	GS&GD	Route A1	Route A2	Route B1	Route B2
🟩 CED	168000	140000	107	-2399	1728	-364

Figure 4.21. Cumulative Energy Demand (CED)

Figure 4.21 Reveals another clear contrast between the two case studies. Copper production in Case A requires massive energy inputs, particularly in pyrometallurgical processes involving smelting and refining at high temperatures. In countries without access to clean energy, this could result in even greater environmental burdens. On the other hand, Route B1 in Case B uses some energy (1727.665 MJ) because there are also smelting and ceramic production which require considerable amounts of energy, but other routes such as Route A2 provide environmental credits, consuming significantly less energy and even delivering net energy savings (-2398.67 MJ). This demonstrates that valorisation, when optimized, can lead to energy-efficient outcomes.

Other Impacts

The remaining environmental impact categories: terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication, show minor differences between Case A and

Case B. However, it is important to note that even in these categories, the valorisation routes in Case B generally provides more favourable outcomes, as indicated by the negative values in Table 4.7. This further emphasizes the environmental benefits of reprocessing tailings compared to the traditional copper mining.

4.5 Case C: Environmental Evaluation of Copper Tailings Reprocessing in the EU

4.5.1 Goal of the Case Study

The case study assesses the environmental performance of reprocessing copper tailings in the EU. It evaluates whether reprocessing these tailings instead of traditional waste management can help reduce greenhouse gas (GHG) emissions and meet future climate goals, particularly the 1.5°C target of the Paris Agreement Adrianto et al. [2023]. The study used prospective LCA to explore the environmental implications of future reprocessing scenarios and their potential to offset primary production.

Objectives

i. Evaluate environmental benefits and trade-offs of reprocessing sulfidic copper tailings.

ii. Estimate large-scale environmental impacts of copper tailings valorisation in the EU.

iii. Assess the potential for secondary product substitution and its effect on reducing the environmental footprint of primary production.

4.5.2 Methodology

The study followed a comprehensive framework for quantifying the environmental performance of tailings reprocessing. The key steps included:

Scenario Development

Adrianto et al. [2023] developed three distinct scenarios of different management approaches for copper tailings based on historical production data and future projections:

i. Business - as - usual (BAU) in 2020 and 2050 which focuses on conventional tailings management, including backfilling operations.

ii. Mineral Valorisation Route (2050) which focuses on using tailings for building materials like ceramics and alternative cements.

iii. Metal and Mineral Recovery Route (2050) focuses on advanced metal recovery technologies and the production of new materials, such as alkali-activated binders.

Modelling Approach

The system-expansion approach was applied, whereby credits for avoided primary production were included when secondary products replaced primary materials. Future energy and technological developments were considered for scenario modelling, incorporating climate mitigation measures based on the Shared Socioeconomic Pathways (SSP2) and Representative Concentration Pathways (RCPs). The Eco invent 3.8 database and 'premise' software were used to model future background systems aligned with the SSP2-RCP 1.9 scenario Adrianto et al. [2023]. The environmental impacts were assessed using the Activity Browser software, covering climate change, toxicity, energy demand, and abiotic depletion potential.

Sensitivity Analysis

To assess the robustness of the results, a sensitivity analysis was performed by changing key assumptions, such as the origin of the substituted product and substitution ratios for secondary products.

4.5.3 Life Cycle Inventory

Copper Tailings Management

In the Business-as-Usual (BAU) and Scenario 1, tailings are managed through landfilling and backfilling, with backfilling expected to increase from 10% in 2020 to 30% in 2050 Adrianto et al. [2023]. Tailings landfilling, which risks heavy metal emissions, was modelled using site-specific inventories.

Valorisation

For future Scenarios 2 and 3, reprocessing routes for copper tailings were modelled using prospective LCA Arvidsson et al. [2018]. Adrianto and Pfister [2022] provided upscaled technology inventories for resource recovery, while energy and material consumption were based on the SSP2-RCP 1.9 scenario derived by Van Vuuren et al. [2012]).

4.5.4 Results and Analysis

Life Cycle Environmental Impacts

Figure 4.22 illustrates two midpoint impact categories, showing the environmental performance of copper tailings management in the baseline year (Scenario 0) and projected future scenarios 1, 2, and 3. Positive values indicate the environmental burden associated with tailings management, including storage and backfill operations. In contrast, negative values represent environmental credits gained from replacing primary metal production and building materials, thus avoiding the impacts of manufacturing.

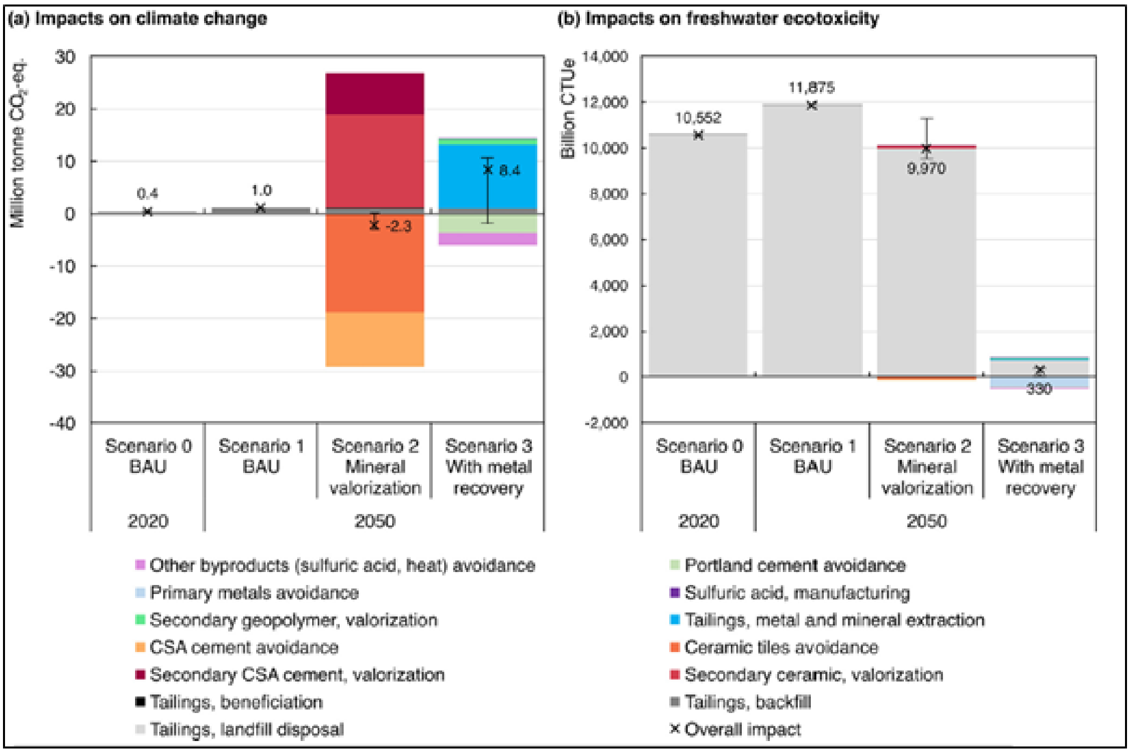


Figure 4.22. Midpoint impact categories: a) Climate change, b) Freshwater ecotoxicity Adrianto et al. [2023]

Scenario 0 and Scenario 1 (BAU)

In Scenarios 0 and 1, tailings management relies heavily on storage and backfill operations, resulting in net environmental impacts. A notable concern is the high freshwater ecotoxicity impacts, driven by long-term contamination from heavy metals leaching into freshwater bodies, potentially leading to acid mine drainage of 10 552 and 11 875 billion (Comparative Toxic Unit for ecosystems) CTUe for the two processes as shown in Figure 4.22. This contamination remains a critical issue in these scenarios due to the absence of valorisation processes. Scenario 1 shows some improvements because it incorporates enhanced tailings management, but still results in net environmental impacts.

Scenario 2 (Valorisation)

In Scenario 2, valorisation efforts lead to a reduced freshwater ecotoxicity impact, with values of 9,970 billion CTUe, lower than those in Scenarios 0 and 1, which are 10,552 and 11,875 billion CTUe, respectively. However, this is still significantly higher than the freshwater ecotoxicity in Scenario 3, which drops to approximately 330 billion CTUe as shown in Figure 4.22. This significant difference is due to Scenario 3's focus on extracting acid-generating compounds and metals from the tailings. In Scenario 2, environmental benefits are predicted by reprocessing tailings to produce secondary materials, such as ceramic tiles and CSA cement. Still it remains susceptible to leaching of acid generating compounds. Scenario 2 still presents considerable benefits, such as the potential to save around 2 Mt CO_2 equivalent by 2050 through the displacement of primary production materials Adrianto et al. [2023].

Scenario 3 (Metal and Mineral Recovery)

Figure 4.22 shows that scenario 3 significantly improves in minimizing ecotoxicity. By extracting metals and converting pyritic compounds into byproducts like sulfuric acid, Scenario 3 effectively reduces the potential for long-term leaching and minimizes hazardous waste generation. Additionally, recovering companion metals from copper tailings helps reduce the environmental burden, especially regarding resource depletion.

4.5.5 Sensitivity Analysis

The sensitivity analysis investigated how variations in key assumptions, such as the origin of substituted products and substitution ratios, influence GHG emissions in the LCA. The study performed a sensitivity analysis by shifting ceramic production away from China to Europe, thereby evaluating the environmental benefits of reducing reliance on China's coal-based electricity.

Impact on climate change

Scenario 2; Ceramics Production

Negative values in this context indicate environmental benefits, as they reflect reduced greenhouse gas (GHG) emissions compared to conventional primary ceramic production. When ceramic tile production is displaced from China instead of Europe, the environmental benefits of Scenario 2 increase by almost ten-fold. This is primarily due to China's heavy reliance on coal-fired electricity for ceramic production, in contrast to Europe's cleaner energy mix, which consists mainly of electricity from renewable sources and natural gas. Figure 4.23 shows that the climate change impact steadily decreases as ceramic production shifts away from countries that rely on coal-based electricity. While displacing all current production scenarios results in a net reduction of climate change impacts, Scenario 2 shows positive outcomes, with the largest environmental benefits achieved by displacing ceramics production in China.

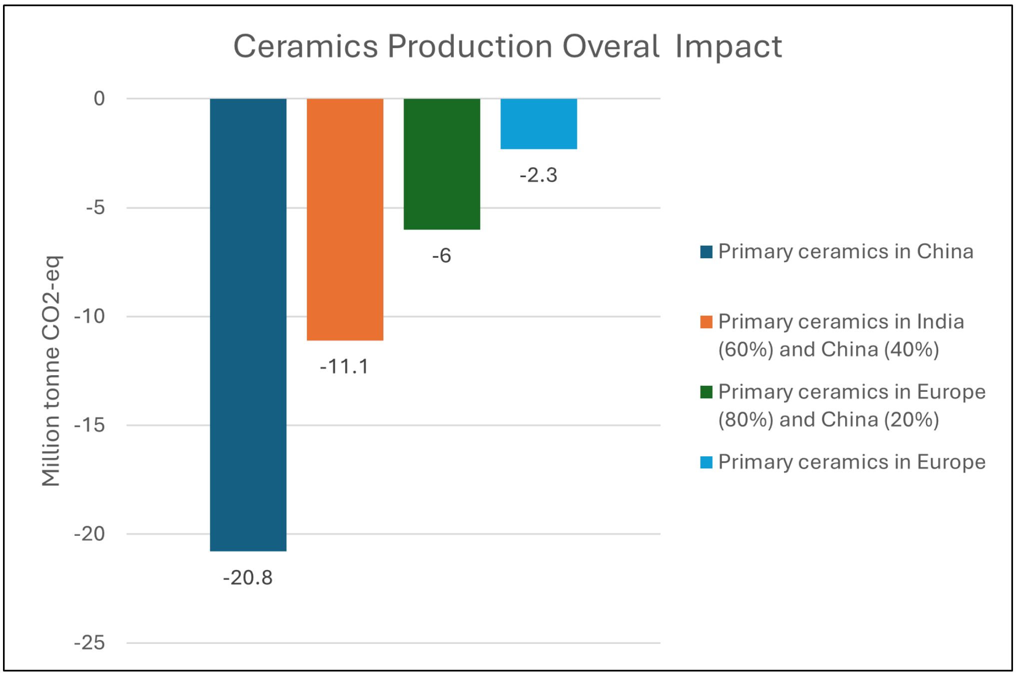


Figure 4.23. Scenario 2 Ceramics Production Overall Impact Adrianto et al. [2023]

CSA Cement Production

Figure 4.24 presents the impact on GHG emissions in millions of tonnes of CO_2 eq when substituting primary CSA (Calcium Sulfo-aluminate) cement production in various regions. A similar trend is observed in CSA cement production as in ceramics, though the difference in GHG emissions between regions is not as pronounced as in ceramics production. Substituting CSA cement production in China results in slightly greater emissions reductions (-2.5 Mt CO_2-eq), compared to other regions like Europe (-2.3 Mt CO_2-eq) and the Middle East (-2.4 Mt CO_2-eq) as shown in Figure 4.24. The lower GHG emissions associated with displacing production in China are again due to the country's heavier reliance on coal-based energy. However, the differences across regions in CSA cement production are smaller compared to ceramics production. Displacing conventional OPC production has significant potential for further reducing GHG emissions by , especially if the process does not include Carbon Capture and Storage (CCS) technologies. This would lead to notable environmental benefits due to the high carbon footprint associated with traditional OPC cement production.

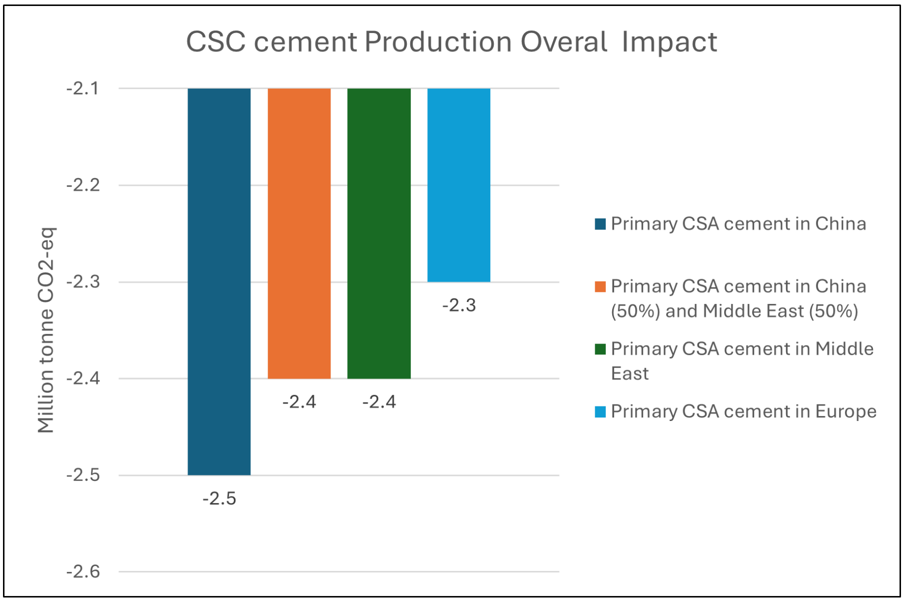


Figure 4.24. Scenario 2 CSC cement Production Overall Impact Adrianto et al. [2023]

Scenario 3

Metal Recovery and Cement production

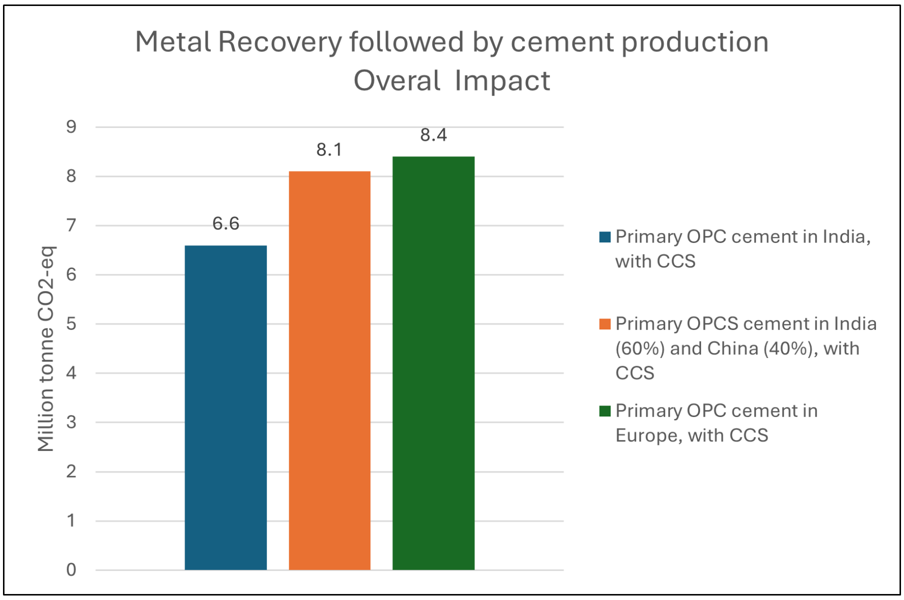


Figure 4.25. Metal Recovery and Cement production Overall Impact Adrianto et al. [2023]

While there is potential to reduce GHG emissions by displacing OPC cement that does not include CCS process in Scenario 3, these reductions are insufficient to fully offset the high emissions generated by secondary metal recovery processes as shown in Figure 4.25. Due to the relatively small volumes of secondary metals recovered in Scenario 3, changing marginal suppliers has a negligible impact on the overall GHG emissions. Metal recovery

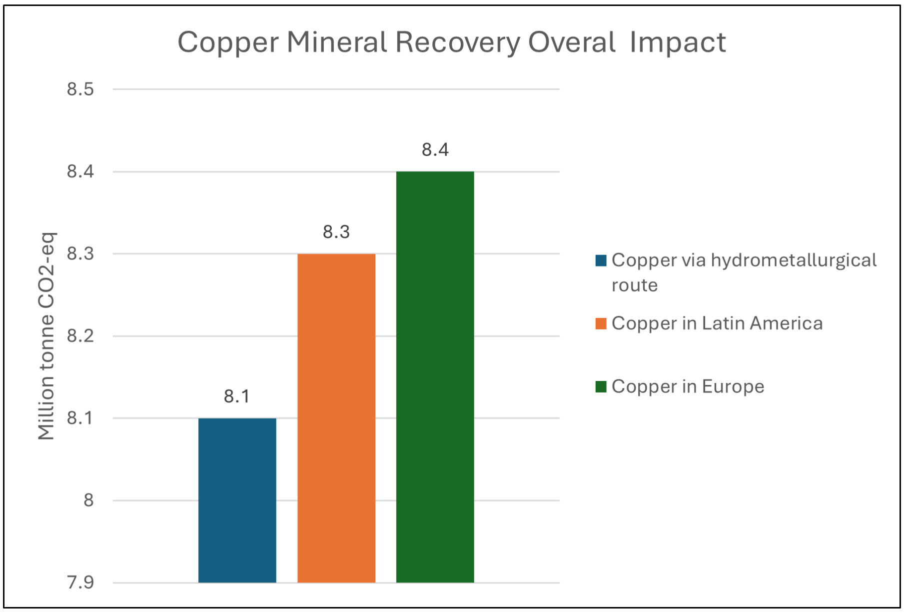


Figure 4.26. Copper Mineral Recovery Overall Impact Adrianto et al. [2023]

Figure 4.26 shows, the overall impact of copper recovery and the GHG emissions associated with various copper recovery methods. The copper recovered using hydrometallurgical route results in the least CO_2 eq, indicating a more favourable environmental performance due to its lower energy consumption than traditional pyrometallurgical methods. Advancements in hydrometallurgical extraction technologies could further mitigate carbon emissions associated with copper recovery. Copper production in Latin America emits 8.3 Mt CO_2 equivalent, showing a moderate carbon footprint that reflects regional energy sources and production practices. Lastly, copper production in Europe has the highest emissions at 8.4 Mt CO_2 eq, which may be attributed to the challenges associated with energy-intensive production methods in Europe.

Substitution ratios for secondary products

Substitution ratios refer to the proportion of primary materials that tailings can replace. These ratios play a critical role in assessing the environmental impacts of different scenarios. In Scenario 2, it is essential to maintain substitution ratios (SRs) for secondary ceramic tiles and (CSA) cement above 0.8 to ensure that the net GHG balance remains negative Adrianto et al. [2023]. This means that for every unit of primary material replaced with secondary materials, at least 80% should be substituted to achieve a beneficial environmental outcome. Effective management of substitution ratios is critical for maximizing the environmental benefits of secondary products and achieving GHG reduction targets. If the substitution ratios fall below 50%, Scenario 2 could perform even worse than Scenario 3. A lower substitution ratio would mean that the negative impacts of using primary materials outweigh the benefits of substituting with secondary products, resulting in higher net GHG emissions.

4.5.6 Conclusion for Case C

This case study highlights the environmental potential of reprocessing copper tailings in the EU, focusing on reducing GHG emissions. Scenario 2 shows significant potential by displacing energy-intensive primary materials, such as cement and ceramics manufacture, with secondary materials derived from tailings. Although Scenario 2 offers a clear reduction in GHG emissions, it comes with a trade-off of higher impacts on ecotoxicity due to handling residual waste from tailings. Scenario 3, which focuses on metal recovery, still exhibits significant GHG emissions due to the energy-intensive nature of the recovery process. However, it offers a marked advantage in terms of reducing ecotoxicity. By extracting heavy metals, producing byproducts like sulfuric acid, and minimizing the risk of toxic leaching and acid mine drainage, Scenario 3 mitigates long-term environmental hazards.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

The valorisation of copper mine tailings is a credible solution to environmental challenges and the recovery of valuable resources. This thesis has provided an in-depth exploration of the technical and environmental aspects of tailings reprocessing, leading to the following conclusions:

Technical Feasibility and Mineral Recovery

Pyrometallurgical processes have demonstrated higher recovery rates than hydrometallurgical methods, with the pyrometallurgy case of Taltal Tailings achieving 74% recovery of residual copper. In comparison, the hydrometallurgy case of Lualo Dam tailings reached 66.2%. However, this increased recovery comes at a higher cost of energy consumption in pyrometallurgy.

Identified Feasible Process

Route A1, which involves separating sulphur-rich and aluminosilicate fractions to produce CSA cement and ceramics, emerged as the most technically and environmentally feasible option. This route offers substantial reductions in greenhouse gas emissions and satisfactory technical performance, making it a strong consideration for further optimization and large-scale implementation.

Environmental Performance

Life Cycle Assessments performed in this thesis reveal that substituting products with materials derived from tailings such as ceramics and CSA cement can significantly reduce greenhouse gas emissions. Case studies, including the reprocessing of sulfidic tailings in Portugal and the EU, demonstrated notable environmental benefits. However, trade-offs such as increased freshwater ecotoxicity and the energy intensity of metal recovery processes affect the overall environmental impact and must be considered.

Trade-offs and Sensitivities

Sensitivity analyses highlight the critical role of transportation distances, substitution ratios, and energy transitions in the sustainability of tailings reprocessing. Maximizing substitution ratios and minimizing transportation distances are critical to achieving optimal environmental benefits.

Challenges and Opportunities

The heterogeneity of tailings compositions is a critical challenge in standardizing reprocessing methods across different sites. This variability in mineralogy requires site-specific approaches, making large-scale, universal applications difficult. However, this challenge also presents an opportunity for site-specific solutions that could lead to the development of adaptable, efficient processes.

5.2 Recommendations

Optimization of Valorisation Routes

Future research should focus on improving the properties of tailings-derived materials, particularly in cement and polymer production. Enhancing their water-resistant properties could increase substitution rates, providing greater environmental and economic benefits. In addition, bioleaching techniques, explored in the Lualo Dam case study in Zambia, should be further investigated to improve copper recovery efficiency as it is a low–energy demanding process.

Advancement of Low-Energy Processing Technologies

Given the high energy demands of metal recovery processes such as smelting, developing and implementing low–energy technologies is necessary. Future research should prioritize innovations in renewable energy use for reprocessing methods, such as ceramics production, to reduce energy consumption and associated greenhouse gas emissions.

Further Case Studies

Although this thesis provides valuable insights, further research is necessary to validate these findings across different regions and operational contexts, as tailings' mineral compositions vary.

Displacement of Production Outside EU Borders

Displacing production from countries with carbon–intensive energy sources, such as those relying on coal-fired electricity, offers significant potential for reducing greenhouse gas emissions. Achieving this, followed by displacing core production processes within Europe, could further reduce emissions by –21.1 Mt CO_2–eq by 2050. This strategy aligns with the EU's sustainability goals and supports the shift toward a circular economy, where waste is reintegrated into production chains.

5.3 Economic Considerations and Future Research

The economic viability of copper tailings valorisation depends heavily on capital expenditure, operational costs such as energy and transportation and the market potential of secondary products. Due to limited data availability, detailed financial modelling and market analysis were beyond the scope of this study. Future research should focus on gathering economic data and conducting comprehensive cost-benefit analyses, particularly for energy-intensive processes like flotation and smelting. Further investigation is required into the market uptake of secondary products such as CSA cement, ceramics, and geopolymers. Understanding the drivers behind market acceptance, including government incentives and technological advancements, is critical to realizing the full economic potential of tailings valorisation. Policies that incentivize the use of secondary materials, could drive market uptake

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