Prospective environmental assessment of reprocessing and valorization alternatives for sulfidic copper tailings

Journal Article

Author(s):
Adrianto, Lugas Raka; Pfister, Stephan

Publication date:
2022-11

Permanent link:
https://doi.org/10.3929/ethz-b-000560787

Rights / license:
Creative Commons Attribution 4.0 International

Originally published in:

Funding acknowledgement:
812580 - European Training Network for the remediation and reprocessing of sulfidic mining waste sites (EC)
Prospective environmental assessment of reprocessing and valorization alternatives for sulfidic copper tailings

Lugas Raka Adrianto, Stephan Pfister

ETH Zurich, Institute of Environmental Engineering, John-von-Neumann-Weg 9, 8093 Zurich, Switzerland

ARTICLE INFO

Keywords:
Life cycle assessment
Prospective study
Environmental impacts
Mine waste
Circular economy
Waste valorization

ABSTRACT

Waste from primary mining operations, especially mine tailings, receive much attention as potential secondary resources that can transform liabilities into resources. The primary intention is to minimize mine tailings disposal problems through volume reduction while recovering secondary resources for industrial materials. However, the environmental benefits and tradeoffs behind these objectives remain unclear. This study conducts a process-based life cycle assessment (LCA) study to investigate multiple reprocessing pathways of copper tailings to co-produce secondary metals and building materials. Four design options representing different value-recovery routes are constructed to assess the environmental burdens of reprocessing chains and the associated benefits from displaced virgin products. This study assesses emerging technologies in a prospective LCA, with projections of bottom-up foreground process modeling and background data like energy supply scenarios. Our analysis reveals that the assessed technologies can only be beneficial when all co-products are utilized. Results indicate that reprocessing may save from 25 up to 930 kg CO₂eq per tonne of treated copper tailings. Potential environmental benefits depend on the reprocessing routes, technology upscaling parameters, and quality of secondary products. We propose recommendations to enhance the environmental performances of mine tailings reprocessing strategies, such as switching to low-impact chemical alternatives and optimizing energy use. Our findings can support the sustainable development of the metal industry in terms of waste management and secondary resource use.

1. Introduction

Worldwide, industrial-scale mining generates a large volume of waste in the form of tailings residues and waste rock. According to the UNEP 2019 report (UNEP, 2019), copper production alone generates around 4 billion tonnes of tailings annually that should be disposed of. This volume is predicted to increase as our metal demands grow over time (Elshkaki et al., 2018; Watari et al., 2021).

Tailings disposal causes long-term environmental pollution through metal leaching or so-called acid mine drainage (Lottermoser, 2010). Furthermore, poor facility management carries dam structural risks, which inadvertently could lead to huge-scale collapses (Franks et al., 2021). The recent 2019 Brumadinho mine accident, among other man-made disasters, was a wake-up call for the entire sector, pinpointing that the long-term storage for such a voluminous waste is not a future-proof solution (Roche et al., 2017). Therefore, pursuing other mitigation efforts is vital to manage mine tailings better, preventing long-term environmental issues and associated hazards.

Better designs for mine waste handling and alternative approaches are already proposed to support cleaner production and environmentally responsible processes. As extensively reviewed by other researchers (Adiansyah et al., 2015; Edraki et al., 2014), examples of feasible technologies are tailings thickening to decrease water infiltration that leads to leaching, desulphurization to limit acid mine drainage, and co-disposal for mine backfill materials. Meanwhile, there are reprocessing strategies for converting tailings to secondary products. The idea has recently become a public interest, in conjunction with the circular economy concept, as it holds the possibility to solve waste problems by turning them into resources (Lêbre et al., 2017; Tayebi-Khorami et al., 2019).

In the context of reprocessing and recycling (Park et al., 2019), tailings are treated to extract metals and mineral residues. Many researchers have already suggested and developed these technologies with a high degree of success in their experiments. For example, one study uses desulfurization flotation techniques to separate sulfur-rich streams (Broadhurst et al., 2015) and generate by-products while simultaneously
decreasing acid mine drainage potential. Another study relies on a combined magnetic – flotation, which can further improve technical performances and extract metals (Huang et al., 2020), and reduce the need for primary mining. If metal contents are high (< 0.5%-wt in copper tailings), other researchers encourage leaching or other separation techniques to maximize metal recoveries (X. Li et al., 2020; Mäkinen et al., 2020; Passos et al., 2021). Some other studies focus on using the mineral fractions, primarily consisting of SiO₂, Fe₂O₃, Al₂O₃, and CaO, as the main ingredients for building materials (Ahmari and Zhang, 2012; Gou et al., 2019; Kim and Park, 2020; Leite Lima et al., 2019). While these experiments show promising results, the research was performed with basic or no environmental assessments. Reprocessing of mine tailings also does not automatically make it ecologically benign, for example, due to higher energy demand and unintended contaminant releases. Given these concerns, a thorough environmental assessment is needed to examine whether these new processes bring the expected environmental benefits, especially when dealing with system-wide perspectives and large-scale applications.

For evaluating the environmental performances of mine tailings reprocessing schemes, one can conduct a life cycle assessment (LCA). This method is standardized and aims to holistically quantify the environmental impacts of resource inputs and emissions over the relevant life cycle phases (ISO, 2006). As such, LCA can fill the knowledge gap in the reprocessing of tailings, made possible by systematically calculating environmental impacts. When multiple secondary materials are generated from different treatment routes, it is also crucial to account for all alternatives. Conventional LCAs – due to their generally retroperpective nature – are not ideal for modeling the environmental impacts of future systems and possible scenarios, which may involve up-scaling of lab or pilot-scale data to large-scale production in the foreground system, as well as projected background data. Prospective/ex-ante LCAs attempt to resolve these issues by adapting early-stage processes in the environmental assessment of modeled future systems (Arvidsson et al., 2018). Thus, with the help of ex-ante LCA frameworks (Tsoy et al., 2020) and upscaling methodologies (Parvatker and Eckelman, 2019) for complementary data provisions, prospective LCA offers a chance to assess the environmental profiles of emerging technologies that are still at a lab scale.

---

Fig. 1. System boundaries of the analyzed systems, representing alternative tailings reprocessing route A (building materials production only), route B (secondary metals recovery and building materials production), and the reference ‘direct landfilling’ route.
The main objective of this study is to construct LCA models applied to copper tailings reprocessing and valorization. We develop life cycle models for an operational mine site with specific waste characteristics, constituting various processing routes based upon continuously refined experiments. These were conducted by research partners in the H2020 ETN SULTAN project (European Training Network for the Remediation and Reprocessing of Sulfidic Mining Waste Sites, www.etn-sultan.eu). This LCA study provided feedback loops for prioritizing technological improvements in processing chains. We also explore the implications of varying key parameters in the processes and evaluate performances with respect to technological changes. Ultimately, the presented study contributes to addressing transparently the environmental performances of mine waste reprocessing for decision-making purposes.

2. Methods

2.1. Goal and scope

This process-based LCA aims to quantify the life cycle environmental impacts of the different reprocessing chains at a tailings site located in Portugal. Currently, tailings are generated from the beneficiation process of metal ores, after which these slurries are sent to the tailings management facility for deposition (Escobar et al., 2021). In this work, the developed LCA model represents various conceptual reprocessing routes, which comprise novel technologies to recover metals from the waste streams and valorize cleaned residues (Fig. 1) and are compared to the reference case without tailings treatment (direct landfilling). The functional units (FU) are then: the disposal of one tonne of sulfidic mine tailings (specifications in Table S1) and the production of materials and other by-products according to reprocessing routes (details in SI section 2). In summary, the FUs include:

- The disposal of 1 t sulfidic tailings
- The production of 1.56 t CSA cement
- The production of 4.1 t ceramics
- The production of 0.69 geopolymer (equiv. to ordinary Portland cement)
- The production of 2.9 kg copper and 7.5 kg zinc
- The production of 110 kg sulfuric acid
- The production of 182 MJ heat energy

We assume zero-burden waste, which excludes the environmental loads caused before the waste generation in the previous life cycles (Ekvall et al., 2007). The system expansion approach is applied, accounting for the credits for the avoided productions (Schrijvers et al., 2020). In the base case, both secondary metals and building materials are assumed to behave comparably similar to the substituted primary products, translating to standard 1:1 substitution ratio (Laurent et al., 2014; Viau et al., 2020). Hence, the impacts of the use and end-of-life phase are excluded in this study. Moreover, relevant information about the use and end-of-life considerations of the resulting secondary products is yet unexplored, preventing any reasonable analysis. The influences of substitution ratios are explored in the sensitivity analysis.

Net environmental impacts of the alternative routes are then calculated as the difference between new reprocessing routes and the reference, comprising: (i) credits for substitution of metals, building materials, and byproducts made from tailings, that otherwise need to be supplied from primary production sources, (ii) credits for prevented long-term landfill emissions to water due to conventional tailings disposal. It has to be noted that the reprocessing system includes additional consumption of resources such as chemicals, aggregates, and other consumables for the production of secondary materials and thus, more than 1 t cement or ceramics are produced per tonne tailings in Routes A-1, A-2 and B-1 (Table 1). All these additional resource consumptions are included in the inventory models.

Table 1 summarizes the processes and routes analyzed in this paper, which are mainly created by gathering direct feedback from researchers working on the reprocessing techniques of the four routes in the project (SULTAN, 2018), and supplemented by literature-based data and discussions with industry representatives.

Primary background data sources were taken directly from the latest Ecoinvent 3.7.1 (Ecoinvent, 2021) cut-off database, accessed using LCA software Activity Browser (Steubing et al., 2020). Overall, the model facilitates a grave-to-gate LCA model incorporating all relevant material and energy inputs to reprocess mine tailings. As for the substituted primary materials production, Ecoinvent 3.7.1 equivalent inventory and literature data were adapted to reflect only primary production routes. Table S26 lists all Ecoinvent 3.7.1 processes used or adapted for the substitution of the primary products. The life cycle impact assessment indicators are described in SI section 3: We included mid- and endpoint indicators (Hierarchist version) from ReCiPe v1.13 (Goedkoop et al., 2013) for a complete set of impact categories, which also allows full aggregation into a single score for interpretation of overall impacts. Additionally we applied cumulative energy demand (CED) (Frischknecht et al., 2015), which is often used in material assessments, and USEtox toxicity-related indicators (Rosenbaum et al., 2008), which are important for assessing tailings impacts on the environments. The selection of indicators aims at covering the most relevant impact categories in the context of waste management and resource recovery from mine waste, besides allowing comparability with other studies in the field.

Table 1

<table>
<thead>
<tr>
<th>Process step</th>
<th>Route A-1</th>
<th>Route A-2</th>
<th>Route B-1</th>
<th>Route B-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental burdens</td>
<td>Beneficiation</td>
<td>Flocculation flotation</td>
<td>Flocculation flotation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Extraction</td>
<td>-</td>
<td>-</td>
<td>MW-roasting and leaching</td>
</tr>
<tr>
<td></td>
<td>Recovery</td>
<td>-</td>
<td>-</td>
<td>MW-roasting and leaching</td>
</tr>
<tr>
<td></td>
<td>Residue valorization</td>
<td>Sulfur rich fraction: CSA cement production</td>
<td>Sulfur rich fraction: CSA cement production</td>
<td>Ceramic production</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aluminosilicate fraction: Ceramic production</td>
<td>Aluminosilicate fraction: Geopolymer production</td>
<td>Geopolymer production</td>
</tr>
<tr>
<td>Environmental credits</td>
<td>Avoided tailings landfill</td>
<td>1 t of sulfidic copper tailings</td>
<td>-</td>
<td>Primary metals (copper 2.9 kg and zinc 7.5 kg)</td>
</tr>
<tr>
<td></td>
<td>Displaced metals</td>
<td>-</td>
<td>-</td>
<td>Primary metals (copper 2.9 kg and zinc 7.5 kg)</td>
</tr>
<tr>
<td></td>
<td>Displaced building materials</td>
<td>Primary CSA cement (1.56 t)</td>
<td>Primary CSA cement (1.56 t)</td>
<td>Primary ceramic roof tile (3.4 t)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Primary ceramic roof tile (4.1 t)</td>
<td>Primary Portland cement (0.69 t)</td>
<td>Primary Portland cement (0.58 t)</td>
</tr>
<tr>
<td></td>
<td>Other by-products</td>
<td>-</td>
<td>-</td>
<td>Primary sulfuric acid (110 kg), heat (182 MJ)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Primary sulfuric acid (110 kg), heat (182 MJ)</td>
</tr>
</tbody>
</table>
2.2. Life cycle inventory analysis: modeling tools

Life cycle data are taken from in-house experiments (SULTAN, 2018), adapted to commercial scale using ex-ante LCA frameworks, and supplemented using secondary data. Technology-specific inventory calculations (Piccinno et al., 2016) are implemented in this study and fulfill the necessary information to complete missing data. Upon previous recommendations, procedures below summarize the inventory modeling hierarchy:

i) When accurate data of mature processes are readily available, this information is directly used.

ii) Judgments from experts and process developers are considered for defining relevant equipment setup and process parameters.

iii) Make use of engineering-based calculations (Piccinno et al., 2016) for estimating inventory inputs.

iv) If data gaps are present after previous steps, similar large-scale applications are used as proxy data.

A summary of the prospective modeling methods and the life cycle inventory calculations can be found in SI-1 Table 2. The following subsections describe the associated technologies and modeling of the reprocessing routes.

2.2.2. Flocculation-floatation

To separate sulfur rich fraction from the original stream (route A), a combined flocculation-floatation process is employed based on the tailings desulfurization study of Broadhurst et al. (2015), complemented with data from project partners. Polycrylamide and xanthate, which act as flocculants and collector agents, are used to improve pyrite separation. While polycrylamide is present in the Ecoinvent database, we incorporate xanthate production from another study (Kunene, 2014).

Overall, the modified beneficiation for tailings imitates industrial flotation techniques (Norgate and Haque, 2010), excluding the grinding fraction—mixes leachate with sodium dodecyl surfactant. Another frother, such as ethanol, is also added to promote foam that physically collapses. This phenomenon helps separate the aqueous parts that contain zinc from the original leachate. Copper and zinc recovery for the upscaled systems is assumed to be the same as its lab-scale results (Xanthopoulos et al., 2021): 85% and 95%, respectively. In scaling up this process, we employ a closed-loop solvent recycling system in ion flotation via continuous distillation (Xanthopoulos and Binnemans, 2021), as similarly done for waste solvent treatments (Amelio et al., 2014; Luis et al., 2013). As a result, 95% of the solvent chemicals are regenerable, with the required energy and chemical inputs, namely electricity, steam, nitrogen gas, and cooling water taken from the software Eco solvent v.1.0.1 (Capello et al., 2007). However, 2.5% of makeup is still required to compensate for the loss of these chemicals. Figure S3 depicts the setup of the ion flotation and precipitation described above.

2.2.4. Sulfuric acid production

Sulfur off-gasses are generated from the pyrite roasting process in route B. A safer alternative to directly emitting these gasses into the environment is its use as feedstock to produce sulfuric acid. Owing to the dense concentration of SO₂ in the off-gas, pyrite roasting has been viewed as an alternative technique to the standard sulfur burning (Runkel and Sturm, 2009). Some adaptations are still needed, however. The entering off-gas must be cleaned through wet cleaning steps. The cleaning step functions to cool down and remove dust particles that are evaporated during the roasting process. 99.8% conversion of SO₂ into sulfuric acid can be achieved in a series of exothermic reactions, occurring in an absorption tower equipped with packed beds of vanadium oxide catalyst. Our model transfers this excess heat to the other processes that would otherwise require natural gas from external sources. The life cycle inventory data for sulfuric acid production is collected from typical best available technologies (European Commission, 2007) in Europe. The process flowchart is presented in Figure S4.

2.2.5. Calcium sulfoaluminate production

Calcium sulfoaluminate cement belongs to the alternative materials that have the potential to lower impacts by using secondary, underutilized calcium and sulfur sources as the principal binding chemistry (Gartner, 2004). Akin to ordinary Portland cement, the CSA production involves raw material acquisition, calcination, and gypsum additions. The main changes in our CSA model relate to input materials and process emissions. The presence of ye’elimite (Ca₂(AlO₂)₂SO₃) as active clinker phase instead of alite (Ca₃SiO₅) brings advantages in decreasing firing temperature by 100 °C – 250 °C during clinkerization of CSA cement (Telesca et al., 2019). The inventory input for clinker materials is
modeled based on Martins et al. (2020, 2021), where highly sulfidic tailings constitute 14%-wt of raw meal mixture. To generate the entire life cycle model at a large scale, we combine our design mix with the industrial CSA plant data. We rely on the work of Ren et al. (2017), which documents the inventory data from operating CSA cement plants in China for both the conventional CSA clinker and waste-derived CSA clinker. The latter case fits our study regarding energy consumption but is adapted to tailings as the raw material instead of slag and bauxite residues (Figure S5).

2.2.6. Ceramic production

Aluminosilicate materials are well-known as suitable inputs for building ceramics, as demonstrated by Veiga Simiao et al. (2021). Their work incorporated up to 10%-wt of tailings as alternative raw materials for substituting virgin material inputs in roof tiles. 0.5 wt% of barium carbonate was added to the roof tile mixture to fix the soluble sulfates, thus preventing drying efflorescence. Upon this basis, the amount of tailings in the ceramic mixtures of industrial production is linearly upscaled from the lab experiments. For other life cycle inventory data, the consumption of alkali activators is linearly upscaled from the lab-scale experiment. A crucial step in the modeling is to simulate the ceramic plant’s performance available in Ecoinvent (Ibáñez-Porés et al., 2011). Aside from auxiliary data, adjustments to the proportion of tailings that replace virgin materials reflect changes in the upscaled ceramic production model (Figure S6).

2.2.7. Geopolymer production

Another use of aluminosilicate materials is the production of geopolymer (Hassan et al., 2019). This product can be a promising candidate to substitute Portland cement to make concrete or mortar, avoiding the need for high-temperature calcination. Based on the work of Niu et al. (2021), tailings-derived geopolymer can be made with suitable alkali activator formulations and reaction settings. We use sodium silicate and sodium hydroxide to mechanochemically activate tailings before the polymer-like structure can form. In our model, the consumption of alkali activators is linearly upscaled from the lab-scale experiments. A crucial step in the modeling is to simulate the manufacturing processes that reflect industrial-scale production with a relevant set of equipment. A recent study by Niu et al. (2021) provide an elaborate approach to upscale the production of geopolymer using a process simulator and generate life cycle inventory data. We specifically adopt an optimized geopolymer making simulation into the current LCA model. The described process is shown in Figure S7.

2.3. Sensitivity analysis

We perform two sensitivity analyses that are related to the process variables, explained in the following:

1) Process parameters in the scale-up activity. We create two spectrums representing best and worst cases to explore the influence of changing key parameters. In general, resource consumption for new processes is tested with (+50%, −25%) deviation from the base values, while mature processes such as ceramic and CSA cement plants have (+25%, −10%) differences. The amounts of recovered metals are varied by defining the overall assumed maximum (95%) and worst (50%) recovery efficiencies. Solvent recycling in the worst cases is reduced to 50% capacity compared to the base case. Lastly, the particulate matter capture systems upgrade can decrease 90% of the emitted particles in the best case. Table S28 lists all altered variables, explanations of assumptions, and references for data in the sensitivity analysis.

2) Transport distance. No transport distance is considered in the base case, assuming all processes take place in the same location. We added lorry (i.e., truck) road transport as additional variables to investigate the effect of delivering raw waste to metal extraction and valorization plants. Short (50 km) and long (300 km) transportation distances are defined based on the manufacturing locations in Portugal (Figure S12).

Additionally, two other sensitivity analyses are conducted, mainly associated with the changes in the background electricity mix and secondary material substitution. We evaluated the implications of changing those factors both, one at a time and simultaneously.

1) Energy transition. According to the EU decarbonization plan (European Commission, 2020), renewables’ shares will increase over time, with progress depending on the country’s efforts. Herein, the Portugal 2030 national energy and climate plan (Environment Portugal, 2019) reflects the changes of the future energy mix. The country will shift from fossil-based power generation (coal 26%, natural gas 24%) to renewables (total contribution of 80%). Details of the energy mix are shown in Table S30.

2) Substitution ratio for material credits. To avoid overcounting benefits from the avoided virgin materials in the base case (1:1), we adjusted the substitution ratio of secondary materials. Following conservative approaches, secondary materials might have impurities or lower technical performances, which decrease the substitutability of the displaced products. Value-corrected substitution ratios for secondary metals were taken from aluminum (Koffler and Florin, 2013) as a proxy for copper and zinc, while the values for secondary building materials are taken from other waste-derived material studies (Hassan et al., 2019; Rigamonti et al., 2020) (ratios reported in Table S29).

3. Results and discussion

3.1. Environmental impact of mine tailings reprocessing

A comparison of life cycle environmental impacts for all reprocessing routes is presented in Fig. 2. In most cases, reprocessing of tailings can result in net negative impacts, but there are also situations where the environmental burdens of reprocessing are more significant than material credits. Residue valorizations for all routes, particularly involving ceramic production, dominate the shares of environmental impacts in almost all categories. This is mainly because of the volumes: 3 – 4 t ceramics are produced for every tonne of tailings input, compared to 1.56 t of CSA cement and a 0.6 – 0.7 t of geopolymer. With relatively better environmental performances than their primary counterparts, the valorized building materials yield benefits that outweigh the resources added to reprocessing in most cases.

Also, the production of secondary metals through leaching and ion flotation (route B-1 and B-2) gives apparent benefits for the toxicity impact category, despite small production quantities for zinc and copper in the overall system. Approximately 3 kg of copper and 7.5 kg of zinc are recovered, avoiding primary copper and zinc ore processing and subsequent tailings disposal. With either scheme (route B), heavy metal emissions from tailings that often cause groundwater contamination can be prevented.

However, the magnitude of benefits should be evaluated correctly for both building materials and secondary metals. They are dependent on the quality of secondary displacing products and the choice of the product replaced in the market. Tailings-derived building products may contain impurities that can lower their ability to substitute primary products or even prevent their application, despite better mechanical performances (Kinnunen et al., 2018; Mabroum et al., 2020). Another aspect is related to base metal production. We use Ecoinvent global market data to represent copper and zinc production in this study. In reality, the emissions from regionalized upstream production vary substantially from one site to another (Adrianto et al., 2022).

To analyze hotspots in every reprocessing step, we present the percentages of contribution in Table 2. Electricity and fossil fuel consumption appear in most reprocessing chains, signifying its importance.
in the foreground system with varying degrees of concern (from below 10% to above 90%). Apart from energy-related contributors, the preparation of chemicals such as solvent mixtures for leaching, surfactants for ion flotation, and alkali activators for geopolymer manufacturing also gives a fair share of impacts due to their energy-intensive production. The hotspot analysis suggests that bringing together energy

![Fig. 2. The environmental impacts for treating 1 t of sulfidic tailings in each evaluated route, including impacts from the reprocessing steps and the impact credits (negative impacts are equivalent to environmental benefits) from displaced primary materials and avoided landfilling. CED = cumulative energy demand, PMFP = particulate matter formation potential.]

**Table 2**
The hotspots in the alternative treatments of mine tailings (individual or combined share above 80%). CC = climate change impacts, CED = cumulative energy demand, FE = USETox freshwater ecotoxicity, PMFP = particulate matter formation potential, SS = Recipe (H, A) aggregated single score. Yellow and red shaded cells indicate values between 40% and 70% and higher than 70%, respectively.
efficiency measures and more sustainable chemical consumption can be guiding principles for process improvement potentials. From the operator’s viewpoint, one can focus on increasing the plant energy efficiency and particulate matter abatement controls at ceramic sites. Waste heat or biomass as a heat source can be considered if the local supply of such fuels is abundant and affordable. The importance of low-impact alkalis (Adesanya et al., 2021) may also overtake sodium hydroxide and silicate’s role as promising constituents for geopolymer production. Ultimately, these all together can be stretched even further when decarbonization is in place, albeit externally reliant. The implications of the above strategies will be exercised in the sensitivity analysis.

3.2. Breakeven analysis: secondary metal production pathway

In situations when there is no valorization due to nonexistent markets for selling building materials, our analysis shows that the recovery of metals alone cannot offset the burdens of tailings reprocessing for most impact categories (Fig. 3). Reprocessing and recovering metals from the current grade of tailings (0.46%-wt copper, 0.92%-wt zinc), according to climate change (CC) impacts, cumulative energy demand (CED), and fossil depletion potential (FDP), intensify overall impacts, with values 2 – 4 times larger than primary metal production. Despite these setbacks, other indicators like particulate matter formation potential (PMFP), metal depletion potential (MDP), and toxicity-related methods exhibit impacts > 90% lower than their primary routes. Notably, the sole metal recoveries are acceptable for all impact categories only when the tailings’ metal concentration is high enough. We find that higher quality tailings with a copper grade of 1.2 – 1.8%-wt are essential to reach the breakeven point of this reprocessing scheme in route B without credits from valorized mineral fractions. Despite its high energy demand, route B through controlled roasting and leaching offers a side benefit of turning original tailings into a more stable residue (Kamariah et al., 2022): another opportunity for mitigating potential environmental impacts associated with sulfidic tailings.

Theoretically speaking, on the one side, this proposal might be preferable for ancient sites where copper concentration in tailings can reach as high as 1%-wt (Nash, 2003). On the other side, it may be challenging for some other tailings where the copper grades are already lower than 0.3%-wt due to technological upgrades or different ore characteristics. According to historical assessments of Chilean porphyry copper tailings (Alcalde et al., 2018), the current production facility has better beneficiation performances than decades ago, with the average tailings copper grades detected around 0.1%-wt. In such cases, mineral valorization pathways will be needed.

3.3. Model sensitivity

Scale-up and process parameters. The results of varying process parameter values in life cycle inventory modeling are presented in Fig. 4. While most of the four reprocessing routes are below virgin production impacts (28 out of 32 indicators) according to base cases, they perform even better than the base cases for all indicators when we applied best case assumptions. Complementary to Fig. 3, applying best case assumptions would reduce impacts notably for CC, CED, and FDP categories, but metal-only recovery still cannot help reach breakeven lines for low-grade tailings (Figure S10). Overall, the sensitivity during scale-up activity causes a range of implications to different routes, inducing changes from 1% to 80% impact additions or reductions.

Routes A-1 and B-1 with the goal to maximize ceramic products reveal high values, surpassing the impact of corresponding virgin for CC, FDP, and CED because of thermal energy and electricity consumption at the manufacturing plant. Next to that factor, particulate emissions are another major cause for PMFP and ultimately ReCiPe (H) endpoint indicators. With proper dust and particulate abatement devices, results indicate that reduction potentials are applicable for these specific routes, combined with other strategies described in the hotspot analysis.

Meanwhile, routes B-1 and B-2 with metals recovery show moderate gains to MDP, human toxicity, and freshwater ecotoxicity indicators—having less than 30% impacts of virgin production even in the worst-case perspective. For both routes, results of several impact categories are highly variable, indicating sensitivity of the result to many novel technologies used in the inventory models. Route B-2, for instance, has the entire portfolio of emerging processes and products, namely MW-roasting, leaching, ion flotation, and geopolymer processes. When applied at a large scale, processes with non-standard equipment such as microwave roasting furnaces and geopolymer plants would entail high uncertainties in the assumptions. Although it appears as the route with the lowest impacts, one should treat the findings with care due to the novelty of the process chain B-2.

Transport distance. When it comes to sensitivity with the transport distances, delivery by truck inflicts a low to moderate increase to overall impacts. Here, the causes are mainly the bulk transfer of raw tailings to a third party for reprocessing, namely the fresh feedstock and cleaned residues to its respective manufacturing plants. Adding 50 km transport by truck contributes to less than 2% of overall impacts. However, for longer distance travels (300 km), specific indicators such as CED, CC, and toxicity-related categories begin showing a 4 – 5 % rise, as shown in Figure S13.

Energy transition. Decarbonized electricity supply improves life cycle performances for all routes, as depicted in Fig. 5. An 11% decrease from the base case is expected for the 2030 electricity mix (blue crosses), notably for impacts associated with energy-consuming processes in the foreground system. Nevertheless, a trade-off exists shall this transition occur. MDP and ecotoxicity indicators show opposite trends, mainly due to extra metal requirements for low-carbon power generation, i.e., solar PV and wind (Kleijn et al., 2011), which lead to background emissions from associated metal mining. This side effect is even more pronounced in a hypothetical 100% solar PV scenario for the electricity of the reprocessing facility (Figure S14), demonstrating the importance of responsible sourcing of electricity supply.

Substitution ratio. Having secondary products of inferior quality reduces the substitution ratios (Table S29) and makes overall environmental performances worse than base cases (Fig. 5, red squares), with an average increase of 14% across all indicators and routes. Consequently, lower secondary material credits – particularly those gained from
displaced ceramic and cement – would render some processing routes unsustainable. When both factors are applied simultaneously, the results are generally situated between impacts induced by them, somewhat balancing the consequences (Fig. 5, green triangles). Nevertheless, this combined effect can also lead to higher impacts than the individual effects, such as for A-1 and A-2 concerning MDP and toxicity indicators.

3.4. Implications for technology designers and policymakers

The results indicate that tailings reprocessing have varying potential to improve overall sustainability. The assessments are meant to provide first-hand calculations for the early-stage technological innovations and enlighten the contributions of these new processes toward sustainable mining. We could derive the following possible implications to technology direction and policy development:

Hotspot analysis highlights research and development needs. By knowing the important drivers of environmental impacts, we can identify the weak parts of the reprocessing chain and propose guiding principles for improving overall sustainability performances.

Build (pilot) facilities near or at the waste sites. Aside from exclusions of transport cost and impacts, this decision would foster synergies among entities, knowledge transfer, and better control of material exchanges at the future industrial symbiosis. Moreover, the established innovation cluster could accelerate scientific research in these areas, which may potentially generate economic revenues during operation or even after primary mining ceases production.

Signal for technological innovations and waste-derived product legislations. Small to medium demo/ pilot enterprises can show evidence for real-life implementations early, where other jurisdictions may mirror...
such a success story. However, central to harnessing benefits are legal standards for products made from waste. As illustrations, introducing quality certifications and minimum shares of recycled materials in public procurement can ensure the viability of mass production and incentivize such plans in the EU and beyond.

3.5. Limitations and future research

This study has limitations that may provide starting points for future research. Some technologies are still at nascent stages, implying a probability of modifications in the long run. Due to a lack of detailed prognosis, these changes and scale differences were partially neglected in the early assessment. Additionally, more advanced technologies may materialize to extract different minerals and metals, such as combined bio-brine leaching to co-produce lead and zinc (Ye et al., 2017) or biosorption techniques to glean rare earth elements (Jin et al., 2017). To understand the true impacts of value recovery pathways from tailings, follow-up investigations of new technologies and constantly monitoring their evolutions are imperative.

Analogous to previous insights, opportunities exist to replace virgin chemicals consumed in the assessed process with bio-based material substitutes. For instance, xanthate could be replaced with cellulose nanofiber materials, an emerging nanocomposite with similar performances made from renewable sources (Sharma et al., 2019). Similarly, other emerging surfactants may substitute sodium dodecyl sulfate, halving its emissions compared to the standard ethylene oxide productions (Nogueira et al., 2019). The compatibility of these bio-based chemicals with the current setups needs to be reevaluated in future research.

The four routes were constructed based on simplified secondary product classifications and mass flow analysis. Mathematical optimization techniques could be developed for this study, constraining the resource consumption and, in parallel, maximizing the environmental performances with defined objectives (Vadenbo et al., 2014). The optimal solutions are probably new pathways with branches of more diverse products not yet captured in the reference routes of this study. For future studies, one may also perform an optimized collection route and then treat the mine waste at designated locations so that financial cost, travel efficiency, and environmental factors can be integrated into the assessment.

As exercised in the sensitivity, the product quality for secondary materials was calculated with value-corrected substitution ratios. To be more precise and guarantee safe application of recycled building materials, one could extend the life cycle phases included in this study by conducting detailed analyses for these specific waste-derived products. We would anticipate successful stabilization of harmful substances in the finished products, as confirmed by other tailings-derived materials studies (Kiventera et al., 2019, 2018; Li et al., 2020). Future work could track potential leaching emissions during the use and disposal phase of the secondary products to explicitly model the downstream impacts for avoiding burden shifts.

4. Conclusions

This research presented the results of applying life cycle thinking tools in an early-stage assessment of mine tailings reprocessing and valorization. The developed assessments provided a solid understanding of the contributions to the environmental profiles of various emerging techniques. There are expected impact reductions among conceptual reprocessing routes, but none of them could avoid burden shifts from a life cycle perspective. The prospective nature of the LCA was able to highlight critical aspects of the process chains that should be enhanced for achieving a more sustainable manufacturing route.

The results suggested that the mineral valorization steps are significant contributors in many impact categories (CC, CED, PMPF), while metal recoveries are particularly beneficial for metal depletion and toxicity-related indicators. The concentration of metals in tailings determines the magnitude of benefits one can get from metal recovery-only routes. In terms of sensitivity, waste transport to the processing site showed a small to moderate contribution to overall impacts, indicating the importance of on-site treatments. On the one hand, decarbonized electricity—powering the whole process—could reduce the impacts of alternative tailings treatment. However, on the other hand, secondary materials with lower quality than substituted virgin products, primarily building materials, may limit the environmental benefits initially gained. Future research could extend the scope of LCA by including the use and end-of-life stages to evaluate impacts more accurately from any downstream processes that wish to incorporate such tailings-derived materials. The early-stage life cycle evaluation can accelerate technological innovations in the mining industry to improve the sector’s sustainability.

CRediT authorship contribution statement

Lugas Raka Adrianto: Conceptualization, Methodology, Software, Investigation, Formal analysis, Visualization, Writing – original draft. Stephan Pfister: Conceptualization, Methodology, Supervision, Writing – review & editing, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

We have made all the raw and calculated data used in the attachments 1 (PDF) and 2 (Spreadsheet).

Acknowledgments

We thank SULTAN early-stage researchers (ESRs) for providing valuable inputs during inventory data collection and process flowsheet development, specifically to: Ana Luiza Coelho Braga de Carvalho, Feliciana Ludovici, Panagiots Xanthopoulos, Nor Kamarjiah, Demian Kalebic, Natalia Pires Martins, Francisco Veiga Simão, and He Niu. We extend our gratitude to Zhengyin Piao (Empa) and Vanessa Schenker (ETH Zurich) who shared their views on the early version of this paper. We thank Prof. Stefanie Hellweg (ETH Zurich) who provided suggestions to the final draft. We also appreciate insights obtained from the mining industry partners about their current waste management practices and potential solutions. The research leading to these results has received funding from the European Community’s Horizon 2020 Programme under Grant Agreement No 812580, MSCA-ETN SULTAN.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106567.

References


Passos, H., Cruz, B., Schaeffer, N., Patinha, C., da Silva, E.F., Coutinho, J.A.P., 2021. Sequential recovery of zinc and copper from acid mine drainage. ACS
Sultan, 2018. Marie Skłodowska - curie actions (MSCA) innovative training networks (ITN) annex 1 to the grant agreement (Description of the action) part B. Proj. Propos. 1–31.


