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LCA as a support to more sustainable tailings management: critical review, lessons learnt and potential way forward

Antoine Beylot^{a*}, Françoise Bodéan^a, Anne-Gwenaëlle Guezennec^a, Stéphanie Muller^a

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Abstract

This article critically reviews LCAs of tailings management, including disposal, use in construction materials and reprocessing for metal recovery. It explores 28 publications considering goal and scope definition, Life Cycle Inventory (LCI), impact assessment (IA), and interpretation. Lessons learnt are discussed: i) tailings final disposal is an environmental hotspot in the production of several metals and manufactured goods; ii) associated key impacts on human toxicity and ecotoxicity are highly sensitive to metals mobility; iii) uncertainty in LCI modelling is rarely addressed, despite expected to be high; iv) compared to classical routes, tailings use in construction materials globally enables environmental benefits, whereas environmental performance of reprocessing needs further exploration. Moreover, mineral resources accounting in LCI of tailings management is classically inconsistently combined with some depletion- or dissipation-based IA. Yet resource dissipation in LCA is promising towards supporting more resource-efficient management. Finally, this article provides suggestions towards improved LCA of tailings management: i) ensuring compliance with standards; ii) balancing metal flows in LCI modelling; iii) rethinking resources “to” and “in” tailings in LCI/LCIA modelling; iv) developing further waste and technology-specific models of emissions from tailings final disposal; v) setting coherent scenarios of future tailings management to consistently account for emissions and resources.

Key words: LCA, tailings, waste, mineral processing, mining, metals

1. Introduction

After extraction, metal ores are treated by comminution and separation techniques, which aim at recovering the valuable minerals in the form of a concentrate while removing the less valuable minerals as a (mineral processing) waste, also called “tailings”. Tailings are solids or slurries which may represent both i) a threat to the environment, due to the toxic substances already in the ore before processing (not recovered from the process) or added through the process chain, and ii) an opportunity in terms of resource production, considering the potentially valuable unrecovered residual metals, by-products or minerals (Bellenfant et al., 2013; Bodénan et al., 2015; Lèbre et al., 2017).

It was estimated that more than 8 billion tonnes of tailings were produced worldwide from the extraction of metals and minerals in 2016, with the largest share (46%) from copper mining (Baker et al., 2020). The number of tailings facilities worldwide tremendously increased in the last 65 years: it doubled between 1955 and 1969, doubled again between 1969 and 1989 and again between 1989 and 2020 (Franks et al., 2020), as driven by growth in demand for metal ores (IRP, 2019) and by a context of declining ore grades (Mudd, 2010). Nowadays, the total number of active, inactive and closed facilities worldwide is projected to be around 8,500 (Franks et al., 2020).

Tailings are most commonly disposed of indirectly, by opposition to direct disposal into rivers, oceans and lakes (Vogt, 2013; Adiansyah et al., 2015). Indirect disposal is mainly performed through conventional dams in which tailings are isolated from the surrounding environment. Tailings containment in dams is faced with a number of challenges, including physical and chemical stability, erosion and seepages, particularly over long-term scales (Franks et al., 2011). In this context, an increasing number of initiatives in the mining sector have aimed at managing waste in a more sustainable way. In particular, thickened tailings, dry stacking and paste backfill techniques have been more and more widely implemented in the recent past. They represent relevant options to ensure more stable and contained waste disposal, while at the same time minimising water, energy and land footprints (Franks et al., 2011; Mudd and Boger, 2013). Moreover, operations for tailings reduction, reuse and reprocessing have been increasingly explored and in some cases implemented on-site (e.g. Bellenfant et al., 2013; Bodénan et al., 2015; Nash, 2020; Araya et al., 2020; Blengini et al., 2019; Bryan et al., 2020; Hubau et al., 2020; Guezennec et al., 2015; Jouliau et al., 2020).

Closure and post-closure represent by far the longest portion of a tailings life cycle (Baker et al., 2020), during which mines do not generate revenue while still potentially being environmental burdens. In the last decade, Life Cycle Assessment (LCA) has been widely implemented to assess the potential environmental impacts of primary metals production in a life cycle perspective, including the life cycle of tailings management. Such studies considered either a large set of metal elements (Nuss and Eckelman, 2014), or a more limited selection (e.g. copper, lead, zinc and silver; Beylot et al., 2021b; Lai et al., 2021).

This increasing application of LCA to the metals sector is part of a more general context of larger implementation of LCA as a support to decision making in the industry and policy fields. In the last three decades, LCA has been integrated into several EU environmental policies, and is expected to be integrated further in future EU policy developments (Sala et al., 2021). LCA implementation in EU policies does not directly involve mining interests, but the modelling of upstream mining processes has major effects on calculated environmental footprints of products using metals (Rader et al., 2019). Tailings management modelling in LCA may therefore have important implications on the way LCA results actually correctly support - or not – industry and policy-decision making towards more resource-efficient and less impacting metal supply chains.

In this context, the objective of this article is twofold. Firstly, it aims at critically reviewing the literature on the application of LCA to tailings management (including disposal, reuse and reprocessing options), with considering both environmental and resource perspectives. Secondly, based on this critical review, it provides suggestions towards better modelling approaches, for supporting sound decision-making for more sustainable metal supply chains.

2. Tailings management in LCA: overview of existing literature

2.1 Approach implemented

This study is based on a literature search performed through Web of Science, online database of peer-reviewed scientific publications in English, in July 2020. Two keywords were combined in the query, and screened within title, abstract and keywords: respectively related to the LCA method (either “Life Cycle Assessment” or “LCA”) and referring to the waste (“tailing”, “tail” or “mineral processing waste”). 37 publications of potential interest to our study were initially identified. Part of them were excluded after a first screening. On the contrary, a number of publications (reports associated with the ecoinvent Life Cycle Inventory – LCI – database and articles published from August 2020), not found initially through the Web of Science search but still considered relevant for the review, were added to the set of publications analysed. Overall, the following analysis is based on 28 publications reviewed (Table 1).

The following sections 3 and 4 aim at critically reviewing the way environmental issues associated with tailings management are taken into account in LCA, distinguishing *i)* studies goal and scope definition (including functional unit definition and resolution of multi-functionality), *ii)* LCI modelling, and *iii)* impact assessment results and their interpretation (contribution, sensitivity and uncertainty analyses). Moreover, beyond this review, a complementary analysis (in section 5) aims at discussing resource issues associated with tailings in the context of the widely debated mineral resource indicators in LCA.

2.2 On the increasing consideration of tailings in the LCA literature

Potential relevance of tailings disposal in the quantification of the life-cycle environmental performances of primary metal production has been acknowledged since 2005 (Althaus and Classen, 2005; Doka and Hirschler, 2005), but it is only more recently that their modelling has been addressed by the LCA community. Developments were initiated in 2008 (disposal of sulfidic tailings) and 2009 (disposal of coal tailings) in the ecoinvent database (Doka, 2008; Doka, 2009), with further refinements in 2018 (Doka, 2018). In parallel, in 2009, the first scientific article dealing with the LCA of tailings disposal was published (Reid et al., 2009), and the topic has known clear increasing interest from 2014 onwards (Table 1). Yet it is particularly noteworthy that the number of existing publications specifically dealing with the LCA of tailings management is significantly lower than that relative to solid waste management systems in a large sense as reviewed by Laurent et al. in 2014 (222 published LCA studies considered in their critical review, with by far a dominant focus on the management of household waste).

Authors	Year	Management technique	Study scope: tailings management case study or broader system life cycle	Ore type	Metallic elements first processed/reprocessed
Althaus and Classen	2005	Final disposal	Broader system life cycle	Metal	NA
Doka and Hischier	2005	Final disposal	Tailings management	Metal	NA
Doka	2008	Final disposal	Tailings management	Metal	(Data mainly from) copper, zinc, lead, nickel and molybdenum mining sites
Reid et al.	2009	Final disposal	Tailings management	Metal	Copper, zinc
Doka	2009	Final disposal	Tailings management	Coal	NA
Nordelöf et al.	2014	Final disposal	Broader system life cycle	Metal	Copper, nickel, gold
Arvesen et al.	2014	Final disposal	Broader system life cycle	Metal	Copper and iron
Peña and Huijbregts	2014	Final disposal	Broader system life cycle	Metal	Copper
Broadhurst et al.	2015	Final disposal	Tailings management	Metal	Base metals
Restrepo et al.	2015	Final disposal	Broader system life cycle	Coal	NA
Matheu et al.	2015	Use as cementitious material	Tailings management	Metal	Not specified
Li et al.	2015	Use as cementitious material	Tailings management	Metal	Iron
Song et al.	2017	Final disposal and Reprocessing for metal recovery	Broader system life cycle	Metal	Copper
Adiansyah, et al.	2017	Final disposal	Tailings management	Coal	NA
Beylot and Villeneuve	2017	Final disposal	Tailings management	Metal	Copper
Harumain et al.	2017	Reprocessing for metal recovery	Tailings management	Metal	Palladium
Doka	2018	Final disposal	Tailings management	Metal	Nickel, copper, zinc-lead, silver, gold and mercury
Ncongwane et al.	2018	Processing for mineral carbonation	Tailings management	Metal	PGM
Vandepaer et al.	2018	Final disposal	Broader system life cycle	Metal	Mainly gold
Dandautiy and Singh	2019	Use as cementitious material	Tailings management	Metal	Copper
Tao et al.	2019	Final disposal	Broader system life cycle	Metal	Lead and zinc
Sarkkinen et al.	2019	Final disposal	Tailings management	Metal	Zinc and copper
Furberg et al.	2019	Final disposal	Broader system life cycle	Metal	Tungsten
Carneiro and Fourie	2019	Final disposal	Tailings management	Metal	Gold

Kossakowska and Grzesik	2019	Reprocessing for metal recovery	Tailings management	Metal	Tailings from two sites : gold and tungsten mines ; reprocessed to produce REE
Grzesik et al.	2019	Reprocessing for metal recovery	Tailings management	Metal	Tailings from two sites : gold and tungsten mines ; reprocessed to produce REE
Wang et al.	2019	Reprocessing for metal recovery	Tailings management	Metal	Tailings from iron-niobium-RE deposit; reprocessed to produce in particular REE, iron, niobium and scandium
Vargas et al.	2020	Use as cementitious material	Tailings management	Metal	Copper

NA: Not Applicable

Table 1: LCA of tailings management in the literature: overview of publications

2.3 Overview of case studies covered

Out of the 28 publications considered in this study, 19 (68%) directly address tailings management as the system under study, while the remaining 9 identify it as key in the environmental performances of other products or systems (Table 1).

2.3.1 Types of ores and management techniques addressed

25 publications address the management of tailings from metal ores extraction and processing, mainly considering copper ores (e.g. Beylot and Villeneuve, 2017), precious and critical metal ores (gold, rare earths elements - REE, Platinum Group Metal - PGM, palladium; e.g. Wang et al., 2019; Ncongwane et al., 2018), and to a lower extent other base metal ores (lead, zinc; e.g. Tao et al., 2019; and iron; e.g. Li et al., 2015 ; Table 1). Three publications consider coal tailings (Adiansyah et al., 2017; Restrepo et al., 2015; Doka, 2009).

Four types of management options are addressed in literature. Final disposal is the main option considered, covered in 19 cases (68%), of which approximately half as a dedicated case study and the remaining half in the LCA/LCI of other products or systems (see section 3). Moreover the reprocessing of tailings for metal recovery and the valorisation of tailings as a supplementary cementitious material for use in construction sector are addressed in respectively 5 and 4 studies (see section 4). Finally, processes for the mineral carbonation of (PGM) tailings are considered in one case study (Ncongwane et al., 2018).

2.3.2 Importance of tailings management in the impacts of the supply-chain

Tailings final disposal is observed to be an environmental hotspot process i) in the cradle-to-gate production of materials and metals: Pb-Zn and Cu concentrates (Tao et al., 2019; Song et al., 2017), copper cathode (Peña and Huijbregts, 2014), cemented carbide (Furberg et al., 2019), and coal (Restrepo et al., 2015); and ii) in the whole life cycle of metal-based products and systems: electrified vehicles (Nordelöf et al., 2014), and offshore grid interconnecting wind farms and customers (Arvesen et al., 2014). This may subsequently affect the environmental impacts of the whole consumption at the level of e.g. a country or a set of countries (e.g. identifying tailings from precious

metal ores as a hotspot with respect to the impact of EU consumption on freshwater eutrophication; Castellani et al., 2019). This in particular depends on the way LCI of tailings management is modelled, and on impact categories at stake; this is further scrutinized in this article (see sections 3 and 4).

3. LCA of tailings final disposal

Among the 28 publications reviewed, nine of them detail models and analyse the environmental impacts of tailings (mainly from metal ores) final disposal (Sarkkinen et al., 2019; Carneiro and Fourie, 2019; Doka, 2018; Adiansyah et al., 2017; Beylot and Villeneuve, 2017; Broadhurst et al., 2015; Reid et al., 2009; Doka, 2009; Doka, 2008). The following analysis mainly builds on these nine case studies. In addition, it takes into account eight publications which consider tailings final disposal in the supply chain of the products or services analysed (Table 1).

3.1 Management techniques, function and functional unit

Most case studies consider the disposal of tailings slurry in conventional impoundments (and to a lower extent tailings from dry processing techniques), with submerging of tailings (as e.g. in Reid et al., 2009) or in some cases including a number of additional/alternative management options. Firstly, Reid et al. (2009) and Sarkkinen et al. (2019) distinguish a number of cover alternatives in their assessment (e.g. a moraine cover, a cover based on biofuel fly ash and steel slag, etc. in Sarkkinen et al.; 2019). Moreover, some authors consider additional process steps prior to disposal: respectively desulphurization aimed at reducing long-term generation of acid rock drainage (Broadhurst et al., 2015) and filtering to reduce slurry tailings moisture content (Carneiro and Fourie, 2019). Only two authors explicitly address disposal techniques which are considered more unconventional in the field, respectively i) submarine tailings disposal in the cradle-to-gate assessment of copper concentrate production (Song et al., 2017) and ii) backfilling after water removal and slag and cement addition (paste backfill during mine operation; Reid et al., 2009).

The function, functional unit and associated reference flow are not always specified in case studies. When specified, the functional unit refers to the “management” (Carneiro and Fourie, 2019; Reid et al., 2009) or “storage” (Beylot and Villeneuve, 2017) of a given quantity of tailings (the reference flow). The latter is set as 1 kg or 1 ton of tailings (e.g. Doka, 2008 and 2009; Beylot and Villeneuve, 2017) or as the mass of tailings generated over a certain timespan, corresponding to the total production at the mine under study (Reid et al., 2009; Carneiro and Fourie, 2019).

3.2 System boundaries

On the one hand, Doka (2008, 2009, 2018) considers only emissions to groundwater and land use in the system boundaries. On the other hand, most other studies claim to consider a broader scope, including material, machinery and energy needed per functional unit (and their associated life cycle environmental interventions), in addition to direct emissions to the environment (Figure 1). In particular, Reid et al. (2009) propose a relatively extensive accounting of inputs (materials and energy) and outputs (emissions to the environment) with distinguishing three mine life cycle phases:

development, operation and closure. Yet a number of specificities may be observed from one study to the other. For example, Beylot and Villeneuve (2017) account for dust emissions (contrarily to most other studies) but in the meantime do not account for material and energy inputs after the construction of the tailings pond (due to lack of data). As another example, Peña and Huijbregts (2014) specifically focus on the life cycle consumption of groundwater and fresh surface water (the “blue water footprint”) associated with the extraction and production of high-grade copper in Chile, and in this respect include losses of water in the tailings dam.

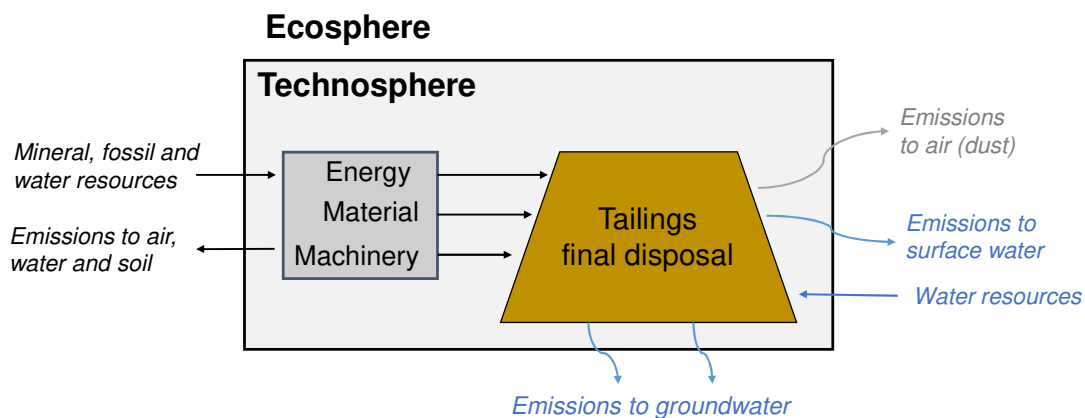


Figure 1: System boundaries in LCA of tailings final disposal, as classically *fully* or *partially* considered in the literature

3.3 Impact assessment and contribution analysis

Most authors address the environmental impacts of tailings disposal with a set of midpoint impact categories, either considering one impact assessment method (e.g. ReCiPe; Tao et al., 2019) or a combination of methods (e.g. USEtox for human toxicity and ecotoxicity, and ReCiPe for the five other impact categories; Broadhurst et al., 2015). Regarding three main impact categories, namely human toxicity, ecotoxicity (freshwater or marine) and freshwater eutrophication, tailings final disposal is a major contributor to the life cycle environmental impacts of a number of products (e.g. Pb-Zn and Cu concentrates, electrified vehicles, etc.) and systems (e.g. offshore grid; Furberg et al., 2019; Tao et al., 2019; Song et al., 2017; Vandepaer et al., 2017; Restrepo et al., 2015; Nordelöf et al., 2014; Arvesen et al., 2014). Additionally, in their specific assessment of the blue water footprint of copper production, Peña and Huijbregts (2014) also identify tailings disposal as a hotspot. The direct emissions of pollutants from the tailings disposal facility to water, including those below thresholds as set in environmental regulations, are responsible for the key contribution of tailings to impacts on toxicity, ecotoxicity and eutrophication (Tao et al., 2019; Furberg et al., 2019; Song et al., 2017; Arvesen et al., 2014; Reid et al., 2009; Broadhurst et al., 2015). Water seepages are moreover identified a hotspot in terms of water footprint (Peña and Huijbregts, 2014). On the contrary, regarding other midpoint impact categories (e.g. climate change, photochemical ozone formation, fossil resource use, etc.), tailings disposal is not identified a hotspot in the life cycle of other products and services. Regarding these impact categories, consumption of energy (electricity, diesel used in equipment) and materials are commonly identified as the main contributors to the impacts of tailings disposal, when accounted for in the inventory (e.g. Carneiro and Fourie, 2019; Reid et al., 2009; Broadhurst et al., 2015).

3.4 Direct emissions to the environment: modelling approaches

Emissions to the environment are a key contributor to impacts of tailings disposal regarding some impact categories. They are classically considered, and sometimes specifically focused at, in the associated LCI modelling. In most cases of publications, the inventory of water emissions to the environment is built from measurements of effluent and leachate concentrations, considering data either from the specific site under study (Reid et al., 2009; Beylot and Villeneuve, 2017), or from a larger set of sites, more generically representative of tailings (Doka, 2008; Doka, 2009; Doka 2018). Still, in one case, Song et al. (2017) perform experimental tests (sequential extraction) to assess metal leaching potential of tailings, before and after remediation. Moreover, in order to calculate the mass of pollutants emitted to the environment, these data of concentrations are multiplied by the volume of effluent and seepage generated over the time period under study, whose values are either obtained from company reporting (Beylot and Villeneuve, 2017), consultant's mine modelling (Reid et al., 2009), or calculated considering a set of parameters and associated global average or potentially site-specific values (Doka, 2008; Doka, 2009; Doka 2018). Potential measures aimed at limiting pollutant release to the environment, including in particular water treatment, are in most cases not specified or their influence both on i) the level of emissions to the environment, and ii) additional energy and reagents consumptions, is not addressed. Finally, as an alternative, Broadhurst et al. (2015) predict the rate and extent to which elements are mobilised, and their subsequent attenuation; e.g. regarding mobilization, with taking into account the time-related reactivity of the forms in which elements occur within solid waste, in particular as a function of redox potential, oxygen concentrations, microbial activity and pH.

Moreover, except in particular Beylot and Villeneuve (2017) who used data from company reporting, most authors disregard dust emissions. Some of them however acknowledge the potential environmental relevance of this flow, especially in arid climates (Doka, 2008) or in the perspective of accurately assessing benefits of revegetation (Reid et al., 2009). Finally, as an overall observation, there is often limited consideration and discussion on the link between the inventory of emissions to the environment and the specific management techniques under study, in a certain planned time-horizon to be defined (as further discussed in section 3.5.3). And when this is addressed, so far no effort for generalization towards technology-specific inventories beyond the case studies at stake.

3.5 Scenarios, sensitivity and uncertainty analyses

3.5.1 Comparison of disposal approaches

Some authors compare tailings disposal approaches on the basis of their environmental performance. In particular, in the case of base metal sulphide tailings, Broadhurst et al. (2015) demonstrate that desulfurization flotation prior to dewatering and disposal implies a reduction in impacts regarding key categories (especially human toxicity and ecotoxicity, thanks to lower zinc mobility after sulphur removal); but at the same time an increase regarding some other categories (e.g. climate change) largely due to electricity consumption. Moreover, copper-zinc mine tailings treatment through water removal combined with slag and cement addition, and subsequent paste backfilling, globally implies larger impacts than in case of their submerging, due to greater amounts of materials and energy consumption (Reid et al., 2009). Finally, a hypothetical electro-dialytic tailings

remediation route (including electro dialysis and thickener, tested at a lab-scale) prior to disposal could significantly reduce impact of tailings in terms of human toxicity, still with potential increase in impact on marine ecotoxicity depending on the impact assessment approach considered (Song et al., 2017).

3.5.2 Sensitivity to electricity consumption

In addition to the comparison of scenarios, some studies address the sensitivity of results to electricity consumption. Broadhurst et al. (2015) show that impacts on climate change and fossil resource use induced by tailings disposal are highly sensitive to electricity consumption. The use of a renewable energy supply (e.g. photovoltaic-based electricity generation) overall contributes to a major reduction in impacts regarding some impact categories (e.g. climate change). It is however also responsible for larger impacts regarding some other categories (e.g. mineral resource use and land use), to an extent that varies among scenarios and case studies (Carneiro and Fourie, 2019; Adiansyah et al., 2017).

3.5.3 Sensitivity to metals mobility and temporal perspective

Impacts of tailings disposal on human toxicity and ecotoxicity are sensitive to the mobility of metals from tailings to the environment (Broadhurst et al., 2015; Tao et al., 2019). Metals mobility firstly depends on tailings mineralogy. In particular the sulfidic nature, or not, of tailings may significantly affect the impacts associated with their disposal and with the whole cradle-to-gate production of metals and materials, regarding some impact categories (Furberg et al., 2019; building on the ecoinvent datasets).

Moreover, metals mobility is also dependent on a time factor. A number of authors therefore distinguish a “short-term” perspective (often set to 100 years as common practice in LCI compilation; see e.g. EC-JRC, 2010) and a “long-term” perspective (e.g. 60,000 years) in their calculations of tailings cumulated emissions (Doka, 2008; Doka, 2009; Doka, 2018; Restrepo et al., 2015; Beylot and Villeneuve, 2017). Impacts of tailings disposal on toxicity and ecotoxicity may be several orders of magnitude larger in a long-term perspective compared to a short-term perspective, with subsequent high influence on the impacts of metals supply chains (Beylot and Villeneuve, 2017) and on the comparison between disposal alternatives (Reid et al., 2009).

At this stage in the literature, there is no common understanding of, and little discussion on, what should be considered the temporal scope to account for tailings emissions to the environment in LCA. For example Reid et al. (2009) consider emissions after the 2-year closure phase until 100 years, whereas much longer temporal perspectives are considered in a number of other studies, in particular 60,000 years in Doka (2008; 2009; 2018) and in Beylot and Villeneuve (2017; referring to the work of Doka, 2008, to set the temporal perspective). Moreover, there is no discussion on any potential reprocessing of tailings in the long-term. The latter would require e.g. energy and reagents to recover metals, and would further affect the tailings content, mineralogical composition and particle size distribution, and subsequently the emissions to the environment associated with tailings disposal (see section 4).

3.5.4 Sensitivity to impact assessment methods

Finally, some authors address the influence of characterization methods on the quantification and interpretation of tailings disposal impacts on human toxicity and ecotoxicity. The choice of the characterization method has decisive influence on the identified hotspot elementary flows (Doka, 2008) and on the level of impact, which may subsequently lead to different conclusions when comparing either two tailings disposal approaches (Song et al., 2017) or two systems for which tailings disposal is potentially key in a life cycle perspective. In particular, Vandepaer et al. (2018) show different hierarchies of performance between Lithium Metal Polymer versus Lithium-ion stationary batteries depending on the way impacts of tailings disposal on non-carcinogenic human toxicity are characterized.

These differences in impact assessment results as a function of characterization methods are driven by different factors, and in particular uncertainty of toxicity and ecotoxicity characterization factors. The latter is primarily due to uncertainty in fate and exposure models (Aziz et al., 2018; Plouffe et al., 2016). This encompasses uncertainty induced by proxies implemented in the method development. It is noteworthy that in USEtox freshwater compartment is used as a proxy for groundwater compartment, which is of potential particular importance in the context of tailings final disposal. Moreover, different substance coverage in different methods may also contribute to discrepancies in impact assessment results. For example among the 39 substances “emitted to groundwater” in the generic ecoinvent 3.7.1 dataset associated with tailings final disposal, only 27 are characterized with a characterization factor in USEtox 2.1; and therefore taken into account in the impact assessment.

3.5.5 Uncertainty analysis

Most studies do not address data uncertainties and their propagation to the impact assessment results. A few authors report that uncertainty associated with some data is large (especially regarding long-term water emissions; Doka, 2009; Doka, 2008; Reid et al., 2009). This encompasses different types of uncertainties according to the authors: high aggregation to derive average models; large inherent variability of data relating to tailings, even at one single mining site; or low quality of models (e.g. linear extrapolation) to fill data gaps regarding post-closure emissions (Doka, 2009; Doka, 2008; Reid et al., 2009). Moreover, in one case study, uncertainty analysis is quantitatively performed building on the ecoinvent pedigree approach, showing that water emissions from tailings disposal imply a relatively high level of uncertainty in the impacts of copper concentrate production on human toxicity and marine ecotoxicity (Song et al., 2017).

4. LCA of the reprocessing, remediation and use of tailings

4.1 Management techniques, function, functional unit and multi-functionality issue

Among the 10 articles from the literature, five study the processing of tailings for the recovery of metals: in particular REE (e.g. Kossakowska and Grzesik, 2019), palladium (Harumain et al., 2017) and copper (Song et al., 2017; Table 1). In these studies, the functional unit is most often set as the processing of a given quantity of a certain type of tailings (e.g. “3.8618 million tons tailings” considered in Wang et al., 2019). The process steps include classical mineral processing operations to recover metals, adapted to target the secondary resources in tailings (Kossakowska and Grzesik,

2019; Grzesik et al., 2019; Wang et al., 2019), and techniques of remediation (phytoextraction; Harumain et al., 2017; and electro dialysis; Song et al., 2017).

Moreover, four other articles study the use of tailings as supplementary cementitious materials to replace cement or to make more efficient the use of cement into mixtures (Vargas et al., 2020; Dandautiya and Singh, 2019; Matheu et al., 2015; Li et al., 2015). The functional unit is generally set as the production of a given volume (or mass) of concrete, mortar or cement, with a specific mechanical performance (e.g. “1 t of Portland cement with 42.5 MPa of strength grade”; Li et al., 2015). This functional unit holds for, and enables the comparison between, concrete (or mortar or cement) produced respectively from classical routes and with using tailings. Vargas et al. (2020) highlight the importance of considering mechanical performances (in MPa) in the functional unit when assessing impacts and benefits of the use of supplementary cementitious materials, including tailings. Finally, Ncongwane et al. (2018) consider processes for the mineral carbonation of PGM tailings, and accordingly set the sequestration of carbon dioxide as the function of the system (and “1000 kg of carbon dioxide” as the corresponding reference flow).

Tailings reprocessing and use enable both the management of a waste and the production of a material (e.g. in the form of a concentrate or of a supplementary cementitious material for use in construction materials). In LCA, the corresponding system is said to be “multi-functional”: it has two functions, but the assessment is performed only in the light of one function of these two. When mentioned in literature, this multi-functionality issue is solved by system expansion: final disposal (and associated impacts; Vargas et al., 2020; Grzesik et al., 2019) or production of the same amount of metals from common primary production routes (Harumain et al., 2017) are considered to be avoided (Figure 2). Yet most authors disregard this issue in their assessment, and only report the environmental impacts of the whole processes at stake (i.e. implicitly associated with all the functions of the system under study).

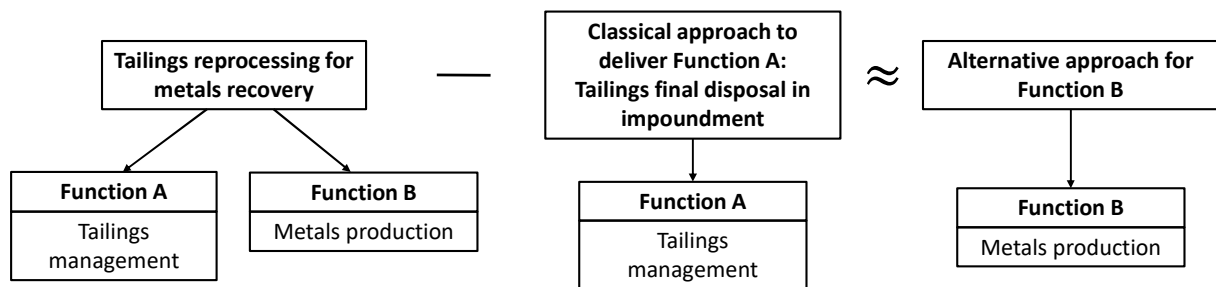


Figure 2: One approach to solving multi-functionality issue in the LCA of tailings reprocessing for metal production

4.2 System boundaries, data sources and representativeness

In the 10 articles from the literature, tailings are explicitly or implicitly considered “burden-free”. This means that all the environmental interventions upstream in the life cycle, generated along the processes which have also generated tailings, are considered to be induced by the products resulting from these processes (in particular, a concentrate) and not by tailings.

The system boundaries generally include all the processes implemented either for the reprocessing of tailings and site rehabilitation (e.g. regarding REE concentrate production from New Kankberg tailings: flotation, magnetic separation, filtration, then residues deposition and land reclamation; Kossakowska and Grzesik, 2019; Grzesik et al., 2019) or for concrete, mortar or cement manufacturing (e.g. Li et al., 2015). All the inputs to the process chain assessed (including e.g. limestone, sandstone, etc. for concrete and mortar production), and their associated upstream life cycle impacts, are considered in the system boundaries. Only some studies also explicitly include excavation (e.g. from the tailings dam) and transport of tailings prior to reprocessing or use (e.g. Vargas et al., 2020; Kossakowska and Grzesik et al., 2019), with in some cases additionally accounting for the requirements in inputs for the treatment of tailings prior to their use as a supplementary cementitious material (e.g. energy requirements for calcination and grinding; Vargas et al., 2020).

Primary data associated with processes are drawn either from on-site operations at an industrial scale (e.g. Li et al., 2015) or at a pilot-scale (Grzesik et al., 2019); from laboratory measurements (e.g. Vargas et al., 2020); or from literature (patents, reports, articles, etc.; Wang et al., 2019; Ncongwane et al., 2018), sometimes implying scale-up to a hypothetical facility (e.g. Harumain et al., 2017; Song et al., 2017) and use of process simulation (Ncongwane et al., 2018). Data are accordingly representative of diverse Technology Readiness Levels (TRLs) as a function of the case studies at stake.

Firstly, regarding the reprocessing, remediation and engineered mineral carbonation of tailings, primary data are mainly related to energy and reagents consumptions along the process chain, per functional unit (Kossakowska and Grzesik, 2019; Grzesik et al., 2019; Wang et al., 2019; Song et al., 2017; Harumain et al., 2017; Ncongwane et al., 2018), although the direct discharge of some pollutants from the process chain to the environment are also reported by some authors (Wang et al., 2019). Moreover, regarding the use of tailings as a cementitious material, masses and nature of ingredients are often explicitly reported and well-sourced (e.g. Li et al., 2015; Matheu et al., 2015), in some case with a design mixture specific to the mechanical performance set in the functional unit to ensure comparisons with classical concrete production (Vargas et al., 2020).

Finally, as a complement, background data associated with inputs other than tailings (e.g. production of electricity, cement, etc.) necessary for the completion of the functional unit under study are modelled based on existing standard LCI databases (e.g. ecoinvent in several studies, including Vargas et al., 2020) sometimes completed with sectoral data from the profession (e.g. databases from the Japanese Environmental Management Association for Industry in Li et al., 2015).

4.3 Direct emissions from tailings to the environment

In the context of tailings remediation, reprocessing and use, three types of emissions from tailings may be considered in the environmental assessment: emissions from tailings “trapped” in concrete, ii) emissions from tailings disposed of after reprocessing (the latter only enables to recover part of the metal content in tailings, with usually relatively limited modifications in quality and quantity), and iii) avoided emissions: the original tailings, which are reprocessed or used, are not directly disposed of. The emissions associated with their avoided final disposal are considered to be saved.

Yet only a few authors explicitly describe and discuss this issue. Firstly, Vargas et al. (2020) modify the ecoinvent dataset relative to tailings final disposal with using specific data on tailings content in

leachable elements, in order to account for the impacts saved thanks to the use of tailings as cementitious materials. They additionally mention that leaching of toxic elements from tailings is reduced by the entrapment of these elements in the cementitious matrix, and do not consider any potential emission from the latter. Moreover, in the case of mineral carbonation of tailings, Ncongwane et al. (2018) do not include the disposal and treatment of waste, considered to be stable and accordingly burden-free. In the case of tailings reprocessing for REE recovery, Grzesik et al. (2019) consider that the reprocessing of tailings enables to avoid their direct disposal (multi-functionality issue solved by system expansion as mentioned above). Yet the tailings quantity and quality are almost unchanged by the implemented beneficiation process. The important environmental benefits (in particular, associated to land occupation and ecosystem quality) reported thanks to the avoidance of final disposal are balanced by the impacts induced by the final disposal of tailings after REE beneficiation (Grzesik et al.; 2019). On the contrary, Song et al. (2017) show that the (hypothetical) electro-dialytic remediation of copper tailings prior to submarine disposal results in changes in the leaching potential of some metals, importantly affecting the cradle-to-gate impacts of copper production in terms of human toxicity (important reduction) and marine ecotoxicity (important reduction or increase as a function of the fraction of metals considered to be mobilizable in the future; Song et al., 2017).

All the issues associated with the accounting of the environmental interventions induced by tailings disposal, as discussed in section 3 (in particular temporal perspective, environmental impact categories considered, etc.), also apply in the context of tailings generated by reprocessing. Yet it is to be additionally noted that in the specific context of tailings reprocessing, in several cases the process is at a development stage. This implies more limited experience and knowledge on their disposal as compared to the more common situation of tailings disposed of after their generation through primary production.

4.4 Contribution analysis

4.4.1 Contribution analysis regarding remediation and reprocessing of tailings

Energy and chemicals consumptions are overall the main drivers of impacts associated with remediation, engineered mineral carbonation and reprocessing of tailings for metals recovery. Firstly, in the case of the production of REE and other metals (in particular iron) concentrates, energy consumption associated with gravimetric and magnetic separation as well as with flotation have important contributions to impacts, which depend on the electricity demand (specific to the production route for the given tailing) and supply mix (Kossakowska and Grzesik, 2019; Grzesik et al., 2019; Wang et al., 2019). Moreover, regarding the flotation step, the impacts associated with flotation reagents add to the impacts induced by the consumed energy (Grzesik et al., 2019; Wang et al., 2019). Similarly, heating requirements and reagents make-up also importantly contribute to the carbon footprint of mineral carbonation of PGM tailings, driving the ranking between the assessed alternative processes (Ncongwane et al., 2018). Finally, the consumption of sodium nitrate for the electro-dialytic remediation of copper tailings is also the main driver of impacts induced by the process for all impact categories (Song et al., 2017). Yet in that case, the impacts of the remediation processes are limited compared to the impacts of the whole cradle-to-gate production of copper concentrate, with the presence and mobility of metals after remediation being the actual drivers of important changes in impacts on human toxicity and marine ecotoxicity (Song et al., 2017).

4.4.2 Contribution analysis regarding use of tailings

Secondly, regarding their application in construction sector, tailings only have relatively limited contributions compared to other inputs in concrete production (in particular cement; Vargas et al., 2020). Indeed, they are considered essentially “burden-free”, with their life-cycle impacts considered to be only associated with their extraction and transport (or even set to 0 when the latter extraction and transport are disregarded). Yet, even in this context, concrete produced with tailings may be observed less impacting than classical concrete only thanks to their avoided final disposal (and more specifically, avoided emissions to water), whose contribution is key regarding freshwater and marine eutrophication and ecotoxicity (Vargas et al., 2020).

4.5 Comparison of use, reprocessing and remediation approaches with classical production routes

The use of tailings as a cementitious material globally enables better environmental performance compared to classical routes for concrete and mortar production (Vargas et al., 2019; Dandautiya and Singh, 2019; Matheu et al., 2015). However, Vargas et al. (2020) additionally state that it is not obvious whether the use of tailings as replacement of cement is environmentally beneficial or not. Environmental performance indicators are in particular dependent on the characteristics of tailings, concrete mixtures and associated mechanical performance, and shall be determined case by case.

In the context of reprocessing and remediation of tailings, environmental benefits compared to classical production routes are more contrasted. Firstly, Harumain et al. (2017) suggest that co-production of biogas, bio-oil, and palladium-containing biochar from plants grown on palladium-containing mine tailings has the potential to result in better environmental performance than primary palladium extraction by present-day mining processes. Yet, while the remediation of copper tailings (thanks to a hypothetical electro-dialytic remediation route) enables to importantly reduce the human toxicity impact of their disposal (and accordingly, of the whole cradle-to-gate production of copper concentrate), it may also imply larger copper mobility and accordingly larger impacts on marine ecotoxicity (Song et al., 2017). Finally, regarding engineered sequestration of carbon dioxide emissions through mineral carbonation, the five alternative processes studied by Ncongwane et al. (2018) all result in higher emissions of carbon dioxide than those sequestered.

4.6 Sensitivity and uncertainty analyses

Sensitivity of results is in particular assessed considering transport distances (with little effect on the environmental performances of the use of tailings to replace cement in concrete mixtures; Vargas et al., 2020), electricity production mix in the United Kingdom and in China (Harumain et al., 2017), and hypothetical improvements in process efficiencies rendering some mineral carbonation routes beneficial in terms of carbon emissions (Ncongwane et al., 2018). Moreover, as an alternative type of sensitivity analysis, Matheu et al. (2015) assess the sensitivity of the impact assessment step to the impact assessment method (respectively BEES and ReCiPe). They show no influence of the method implemented on the conclusions supported by the environmental comparison (namely, lower impacts of mortars produced with tailings compared with ordinary Portland cement hydraulic mortar).

Yet no study performs any uncertainty analysis. This is despite a number of case studies relate to technologies at a low TRL (as mentioned in section 4.2); i.e. in a development stage particularly adequate to support environmentally preferable outcomes despite commonly least available data and greatest uncertainty (Bergerson et al., 2020).

5. Mineral resources in LCI and LCIA: issues for tailings

5.1 Resources extracted and depleted

5.1.1 Mineral resources in LCI

As defined by the United Nations Environment Program (UNEP) Life Cycle Initiative, “mineral resources” in LCA are “chemical elements (e.g. copper), minerals (e.g. gypsum), and aggregates (e.g. sand) as embedded in a natural or anthropogenic stock” (Berger et al., 2020). On the one hand, there is a global consensus in standard LCI databases (e.g. ecoinvent and Environmental Footprint databases) to account for “mineral resources” as elementary flows extracted “from ground” (in the ecosphere) for use in the technosphere, with quantification in units of mass. “Mineral resources flows” in LCI are therefore flows from geological stocks to the technosphere, with occurrence only in extractive steps of the life cycle of systems. On the other hand, there are still different views on what could/should be considered the resource elementary flows in LCI datasets; i.e. in which form (e.g. mineral or element?) and quantity (e.g. all metals contained in the ore or only the extracted ones?).

5.1.2 Mineral resources to tailings

The definition of the Life Cycle Initiative enables to account for any element in a “natural stock”, including the share of mineral resources extracted from ground and ultimately transferred to tailings due to process inefficiencies (as e.g. accounted for in the ecoinvent database for metals targeted by extraction activities; Weidema et al., 2013). Yet it is noteworthy that there are multiple definitions of “natural resources” and “mineral resources” as provided in environmental, economic, social and law studies (Ardente et al., 2019). These may lead to different understandings of the share of resources transferred to tailings. In particular, the CRIRSCO definition, used in the Mining and Metals sectors, states that “a Mineral Resource is a concentration or occurrence of solid material of economic interest in or on the Earth’s crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction”; CRIRSCO, 2012). Considering this definition rather than that of the Life Cycle Initiative, one may therefore argue that the share extracted and not recovered in the concentrate (i.e. transferred to tailings) shall not be considered a mineral resource in LCI.

5.1.3 Mineral resources in tailings

Whereas the definition of the Life Cycle Initiative refers to any “anthropogenic stock”, the share of metals contained in tailings are never explicitly flagged “mineral resources in tailings” in LCI datasets. The composition of tailings is sometimes reported in the LCA of tailings management options, for example in order to support the derivation and interpretation of emissions from tailings disposal facilities to the environment (e.g. Doka, 2008). But contrarily to mineral resource flows “from the ecosphere to the technosphere” as commonly inventoried in LCI datasets, there is usually no inventory i) of the “resource content” of tailings and ii) of resource flows “from the technosphere to the technosphere” in case metals are extracted from tailings (an “anthropogenic stock” recalling the terms of Berger et al., 2020).

5.1.4 Inconsistency with depletion-based impact assessment

The Abiotic Depletion Potential (ADP) method, considering the ultimate reserve (Guinée et al., 2002; van Oers et al., 2002), is one of the most widely applied impact assessment approaches to account for the impacts associated with mineral resource use in LCA (e.g. recommended by the UNEP Life Cycle Initiative; Berger et al., 2020; and by the European Commission; Zampori and Pant, 2019). It relies on the concept of “depletion”: the extraction of a resource from the Earth’s crust is considered to contribute to its exhaustion (“depletion”; Figure 3).

In case the LCI of primary metals production chains accounts for the whole mass of target metals extracted from ground, including the share transferred to tailings (e.g. as in ecoinvent), then the application of the ADP method is inconsistent. Indeed metals transferred from the Earth’s crust to the tailings disposal facility will be “back to the crust” at some point in time, when the disposal facility is not managed anymore. Therefore, the disposal of target metals in tailings disposal facility shall be seen as a transfer from the Earth’s crust to the Earth’s crust, by definition not contributing to the depletion of the geological stock. Instead, LCIs accounting only for the produced minerals as the mineral resource flows, i.e. excluding metals transferred to tailings, are consistent with the implementation of the ADP method.

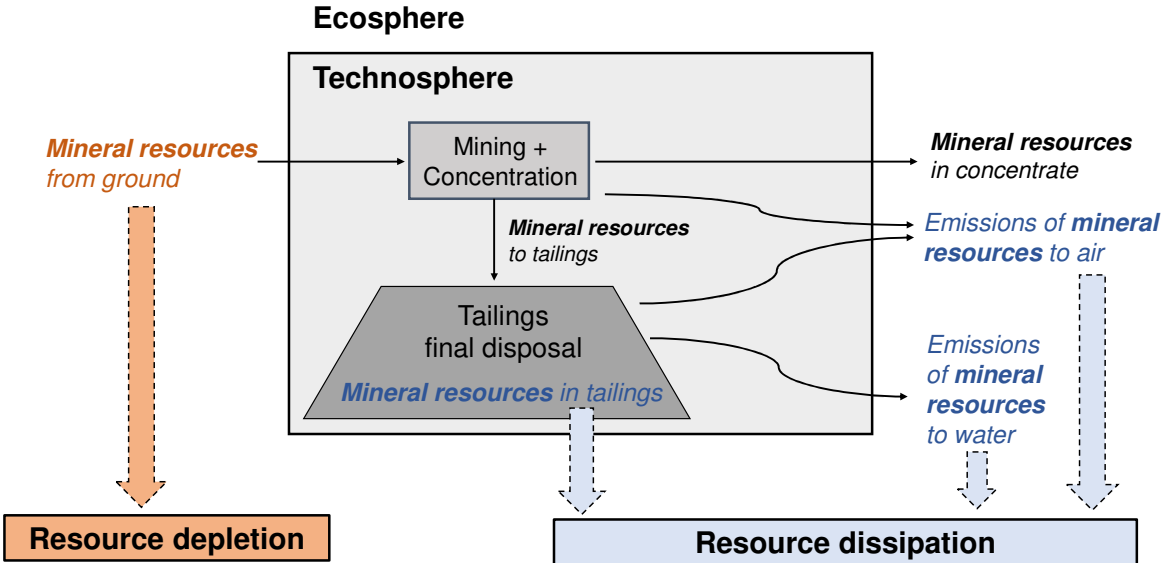


Figure 3: Mineral resource flows along the production of a metal concentrate: potential contributions to “resource depletion” and “resource dissipation” impact categories

5.2 Resources dissipated

5.2.1 “Resource dissipation” and its consideration in current LCI datasets

The concept of resources (or materials) dissipation after their use in the technosphere has been increasingly considered a potential better way to account for impacts on mineral resources in LCA (e.g. EC, 2018). Building on their literature review, Beylot et al. (2020b) defined dissipative flows of abiotic resources as “flows to sinks or stocks that are not accessible to future users due to different constraints”.

Metal resources transferred to tailings final disposal facilities, and more generally any dissipative flow of resources, are currently not flagged as “dissipative” in LCI databases, even if sometimes *implicitly* considered “dissipative”. For example in the case of copper concentrate production in the ecoinvent database, approximately 19% of the copper accounted for as a resource extracted from ground is transferred to a tailings disposal facility, from which it is implicitly considered inaccessible (no reprocessing/recovery of metals from tailings in the ecoinvent database; Beylot et al., 2020a). In order to explicit the accounting of resource dissipation in LCA, two main operational approaches have been recently developed (hereafter referred to as the “SUPRIM” and “JRC” approaches), building on diverse rationale with subsequent diverse implications for metals in tailings.

5.2.2 SUPRIM operational characterization factors

The SUPRIM project in particular developed an operational set of preliminary characterization factors for the impact category “environmental dissipation” (van Oers et al., 2020). Considering a very long-term perspective (set “somewhere between 100 years and infinite”), dissipation to the environment is considered the dominant mechanism for loss of elements from the accessible stocks. Any resource in “hibernating stocks” in technosphere is on the contrary considered to be accessible at some point in time thanks to economic and technical developments (EDP approach “over the very long term”). This implies that metals contained in tailings are not considered to be dissipated if they remain in tailings disposal facilities. Instead, any metal emitted from tailings to the environment is accounted for as “dissipated”, whether this metal was targeted in the concentration process chain and subsequent metallurgy, or not.

The application of the SUPRIM operational approach to the context of tailings raises three main issues. First, it builds on the assumption that any resource in “hibernating stocks” (including tailings) will be accessible at some point in time. This is not in line with:

- i) classical modelling of tailings treatment at the LCI stage: there is in particular no consideration of tailings reprocessing in standard LCI databases. This means that in the vast majority of LCAs of products and systems, today, tailings are considered to be disposed of without valorisation; said in other words, “hibernating stocks” in tailings are usually considered inaccessible at the LCI stage, in contradiction with the assumption made at the LCIA stage in the SUPRIM operational approach;
- ii) current practices and knowledge on future practices: e.g. the recovery of critical and other raw materials from extractive waste is not a widely diffused practice in the EU yet (Blengini et al., 2019). Assuming that economic and technical developments will make the whole (100%) “hibernating stocks” in tailings accessible on the very long term is not supported by any evidence. As of today, it can be considered as realistic as many other assumptions on

future levels of accessibility (from levels closer to 0%, to 100% as here considered by van Oers et al., 2020).

Secondly, the way the concept of “resources” is understood (that is, any metal in tailings is considered a resource, dissipated when emitted to the environment) is consistent with the wide definition of the Life Cycle Initiative for “mineral resources”. However it is noteworthy that the underlying concept of “resources” is often understood differently in the LCA field; e.g. in the ecoinvent database which considers only the “target metals” as “mineral resources” extracted, whereas the other metals in the ore, not targeted and transferred to tailings, are not considered “mineral resources”.

Finally, this operational approach relies on the accounting of emissions from tailings to the environment, in particular to groundwater. Therefore the issues (including uncertainty) associated with the accounting of emissions of metals to the environment in LCIs of tailings final disposal may not only largely affect the assessment of impacts on human toxicity and ecotoxicity (see section 3), but also the assessment of mineral resources “environmental dissipation”.

5.2.3 JRC suggested approach

Beylot et al. (2020a; 2021a) suggest to report the dissipative flows of mineral resources, in mass units, at the unit process level. Considering a so-called “short-term perspective” (25 years), any flow of resources to i) environment, ii) final waste disposal facilities and iii) products in use in the technosphere (with low functionality) shall be reported as dissipative. In this respect, any chemical element from ground targeted through an extractive process-chain (flagged as “mineral resources” if considering the ecoinvent nomenclature), and ending in tailings for final disposal, is considered a dissipative flow (e.g. copper in tailings from copper concentration). On the contrary, any metal non-targeted that ends in tailings for final disposal (e.g. any trace of mercury, cadmium, etc. not targeted through copper concentration) is not a dissipative flow. Moreover, the approach suggested by the JRC can also be implemented considering longer-term perspectives. In that case, only a share of metals in tailings may be considered inaccessible to future users; i.e. dissipated. As a proxy to derive first estimations, Beylot et al. (2020a; 2021a) for example assumed that emissions from tailings to the environment are the only flows of resources “not accessible to future users” (i.e. dissipative) in a long-term perspective. This implied a much lower contribution of tailings final disposal to resource dissipation in the cradle-to-gate production of copper concentrate compared to the *short-term* perspective. Regarding such longer temporal scopes, the parameters, criteria and thresholds to be assessed to define a resource as “dissipated” or not (in particular in a tailings disposal facility) still need to be further discussed and defined (Beylot et al, 2020a; 2021).

5.2.4 “Resource dissipation” in tailings: potential and perspectives

Developments on the accounting of mineral resource dissipation in LCA are not specifically dedicated to tailings. Yet discussions on the definition of resource dissipation has led to a number of considerations regarding tailings and the potential accessibility/dissipation of the metals they contain (Beylot et al., 2020a; 2021a). The accounting for resource dissipation in LCA (Figure 3) would in particular support effective actions to reduce the impact of mineral concentration chains on resource use. This would indeed help to identify hotspot process steps for metals “loss” or “dissipation”

(especially, in tailings; Beylot et al., 2021b) with focus not only on the metals targeted by concentration processes but also on some potential by-products for which the extraction may be technically feasible but not economically viable.

Moreover, the concept of mineral resource dissipation additionally offers perspectives for better capturing the resource issues associated with the use of tailings to replace cement. Indeed the latter globally enables better environmental performance compared to classical routes for production (as discussed in section 4.5), in particular thanks to metals entrapment in concrete which may limit any associated emission to the environment. Yet metals entrapment may also simultaneously imply more limited possibilities to ever recover the contained resources in the future (in particular due to lower concentration and larger mixing with other minerals), which may be potentially well-captured by one resource dissipation indicator in LCA.

6. Tailings management in LCA: potential way forward

This current state of play in literature leads to the identification of a number of key issues to be addressed towards complete and consistent modelling of tailings management in LCA. The following sections sum up these issues and a potential way forward from the short-term (regarding compliance with LCA standards; in section 6.1) to longer terms (sections 6.2 to 6.5).

6.1 Ensuring compliance with LCA standards

Any deviation from LCA standards and guidance may affect the results quality and hamper any attempt to support sound decision-making. Building on this review of LCA applied to tailings management, it appears crucial that analysts pay attention to the following four issues:

1) in many instances, the functional unit is not clearly stated. Regarding case studies on tailings final disposal, this generally has limited effect as the functional unit is often *implicitly* meant as the disposal of a given quantity of tailings. Yet this is a key issue regarding case studies on tailings reuse and reprocessing, which involve two functions or more. The absence of discussions on the system function(s) prevents any correct solving of multi-functionality issues, which may largely affect modelling and environmental impact calculations;

2) transparency on data and justification on modelling choices shall be improved. This in particular means properly disclosing datasets and justifying the rationale for their potential incompleteness;

3) the scope of impact categories addressed shall be considered in the interpretation of results. Tailings final disposal is a major contributor to the life cycle environmental impacts of a number of metal-based products and systems regarding human toxicity, ecotoxicity and freshwater eutrophication. Accordingly, regarding both tailings management and metal-based products and systems, LCA studies focusing for example only on climate change disregard potentially key environmental issues;

4) in the results interpretation step, a limited number of studies include sensitivity analyses, and even less uncertainty analyses. This is particularly key in a context where the modelling of tailings management in LCA is recognized by a number of authors as highly uncertain, while at the same time potentially significantly affecting the life cycle environmental performance of other systems for some impact categories. Uncertainties of the data implemented in tailings management LCI modelling shall be properly considered and propagated to the impact assessment results.

6.2 Balancing metal flows in LCI datasets of primary metal production

In order to ensure the correct accounting of elementary flows from/to the environment, LCI datasets shall be compliant with mass balance identities. This for example implies that, regarding the case of metal concentrates production, the mass of targeted metals in the input run-of-mine ore shall be identical to the sum of the masses in the output flows, respectively in the output products (concentrates), in waste (tailings) and as direct emissions to the environment. Yet compliance with mass balance identities is not always ensured in LCI datasets (for example in the case of copper tailings from copper concentrate production in the ecoinvent database; Beylot et al., 2020a), meaning inconsistencies in the inventories and subsequently in the impact assessment and results interpretation.

Mass balance reconciliation, at the substance level, appears key to enable the development of coherent LCIs, consistently tracing resources along the process chains. It may be complemented with modelling, for example using process simulation as in Bodin et al. (2017), in order to estimate some missing flows. Mass balance reconciliation and modelling would accordingly support improved LCI data quality, in particular ensuring consistent accounting of metal flows transferred from ore processing to tailings management. This would globally reduce LCI datasets uncertainty, and subsequently uncertainty of LCIA results in particular with respect to i) impact on mineral resources (depletion of the resources stocks in ground, and dissipation in tailings) and ii) human toxicity and ecotoxicity impact categories for which the metal content in tailings is a key driver of environmental burdens.

6.3 Rethinking “resources to/in” tailings, in LCI datasets

Diverse LCI-modelling approaches to the notion of resources in ores, of which a share may be considered (or not) transferred to tailings, result in diverse potential impacts on resource depletion and dissipation. It is therefore key to transparently define which substances are considered to be *resources* extracted from ground in the system under study, and in particular whether metals extracted from ground and transferred *to tailings* are *resources*. Moreover, in order to define whether these resources are dissipated or not, it is then needed to set whether they are accessible to future users (in a given time horizon) or not.

Several approaches to the “resource-status” of metals *to* and *in* tailings may arise from the LCA community. It is key to raise the level of transparency on this issue in studies: in a context where tailings management is a step in the life cycle of a tremendous number of products and systems, more transparent modelling will ensure better consistency between studies and more adapted results interpretation regarding resource indicators.

6.4 Designing new models for the LCI of tailings final disposal

6.4.1 Key exchanges to be focused on in the inventory

Tailings final disposal has a large contribution to the life cycle impacts of a number of products and services regarding human toxicity, ecotoxicity (freshwater or marine), freshwater eutrophication and to a lower extent water impact categories. It is therefore encouraged to further improve the LCI of tailings final disposal primarily by addressing the direct emissions from tailings to the environment which mainly contribute to these impact categories (metals to groundwater in particular). Instead much less effort shall be put on collecting data associated with energy and material uses. Recent research which aimed at combining geochemical modelling with LCA in order to better model metals emissions from tailings disposal to the environment in the long-term (Adrianto et al., 2020; Muller et al. 2019) appear particularly promising in this context. Moreover, as a function of the type of tailings disposal, a specific attention may be given to some emissions to the environment (e.g. regarding rare earth minerals collocated with naturally occurring radioactive material).

6.4.2 Towards (more) waste and technology-specific models of emissions to groundwater

The mobility of metals from tailings to the environment depends on a number of site-specific conditions. In particular, these include:

- the tailings mineralogy and particle size distribution, which are dependent on the ore treated and on the mineral processing operations implemented;
- any potential measure aimed at limiting the release of pollutants to the environment, in particular as a function of the local regulatory conditions. Active water treatment (use of reagents and energy) and passive/semi-passive water treatment commonly aim at limiting the emission of pollutants to the environment before and after the closure of the site, and shall be considered in the modelling. Similarly, specific measures such as revegetation may enable to limit the emissions of dust to the environment;
- environmental conditions, such as climate or geochemical backgrounds.

As of today in the LCA literature, only a limited number of authors account for, or more generally discuss, these aspects in their studies. There is the need to develop waste- and technology-specific LCI models, with a portfolio of techniques as large and representative as possible, as is the standard for other waste management techniques (e.g. Municipal Solid Waste incineration; Beylot et al., 2018). This calls for more case studies and dedicated LCI models, considering a large scope of disposal techniques including:

- conventional techniques: rehabilitation, revegetation and capping of dams; recovery of dam seepages on a more or less long-term basis; and submerging;
- alternative treatments: e.g. paste and thickened tailings; direct disposal into rivers, oceans and lakes; backfilling.

6.5 Setting a consistent framework to account for resources and emissions

The accounting for resource and environmental issues in the LCA of tailings shall be based on a common, consistent, framework. This first means that the same masses of metals in tailings shall be considered to compute both the emissions to the environment (in particular, to groundwater) induced by tailings disposal, and the tailings content in resources. Moreover, the resource and environmental assessments shall be based on consistent timeframes (as discussed in section 6.5.1) and associated scenarios of potential future management of tailings (section 6.5.2).

6.5.1 Consistent timeframes

In the LCA literature, two main temporal perspectives are considered for the modelling of emissions from tailings final disposal to the environment: respectively “short-term” (often set to 100 years) and “long-term” (e.g. 60,000 years), with tremendous effect on the associated environmental impacts (section 3). Similarly, diverse approaches of accounting for resource dissipation consider diverse temporal perspectives, from “short-term” (e.g. 25 years) to “long-term” (e.g. “somewhere between 100 years and infinite”), over which resources are considered to be inaccessible to future users (“dissipated”), or not (section 5).

There shall not be any single temporal perspective for, so-to-say, “correctly accounting” for resource and environmental issues associated with tailings management in LCA. Diverse temporal perspectives may be of diverse interests to decision-makers, while highly affecting impact assessment results. Therefore when tailings management is part of the system under study, the temporal perspective(s)

shall i) be explicitly stated in the goal and scope definition, in line with the objectives of the study's commissioner, and ii) be set to consistently address both environmental (in particular toxicity, ecotoxicity) and resource (dissipation) issues. Several additional temporal perspectives may moreover be considered and tested as support to sensitivity analysis.

6.5.2 Consistent scenarios of potential future management of tailings

The dissipative nature of a resource flow depends on the temporal perspective considered and, in particular in case of long term perspectives, on scenarios of potential future recovery. Different scenarios of tailings management in the future may imply different evaluations of the potential for resources accessibility (and dissipation). Yet, despite the potential key importance of such scenarios, so far studies dealing with resource dissipation in LCA have not properly addressed this issue.

In the meantime, in LCI databases final disposal of tailings in conventional impoundments is the main, and often only, management option. This is consistent with the general aim of LCI databases to represent the main current processing routes. Yet, this implies some potential inconsistency between approaches: on the one hand, in the LCI modelling step using standard LCI databases, tailings are considered to be disposed of in impoundments with no perspective for resources recovery; whereas on the other hand full recovery of resources in tailings in the future is considered in some approaches developed to account for mineral resource dissipation at the impact assessment stage. Scenarios of future tailings management shall therefore be developed, common to i) LCI modelling, in particular regarding future emissions of tailings final disposal, and to ii) resource dissipation impact pathway, in particular regarding how far resources in tailings are accessible (or not) to future users. These scenarios would support consistent LCI modelling and resource dissipation impact assessment regarding tailings management. This will necessarily come along with different levels of confidence: larger for the relatively well-known short-term compared with any modelling regarding a long- to very long-term perspective.

7. Conclusions and perspectives

Quantification of environmental and resource impacts and benefits of tailings management through LCA has attracted increasing interest in the last decades. This article explores 28 publications and highlights that: i) tailings final disposal is a major contributor to the environmental impacts of the production of several metals and manufactured goods; ii) associated key impacts on human toxicity and ecotoxicity are highly sensitive to metals mobility; iii) uncertainty in LCI modelling is rarely addressed, despite expected to be high; iv) compared to classical routes, tailings use in construction materials globally enables environmental benefits, whereas environmental performance of reprocessing needs to be further explored. Recent accounting for mineral resource dissipation in LCIA indicators is moreover promising towards effectively supporting more resource-efficient tailings management.

This article further suggests a potential way forward towards representative, robust and consistent consideration of tailings management in LCI and (mineral-resource oriented) LCIA models. Better modelling of tailings management is necessary to better support sound, environmentally and resource-driven, decision-making not only at the process and mining industry-levels but also at the

product level, in a context where LCAs increasingly form the basis for the selection of materials in products.

These developments will require more LCA case-studies, considering a range of tailings types and associated management techniques sufficiently large for models to be representative and complete. These models shall benefit to (and may build on) other life-cycle thinking approaches like Material Flow Analysis, in which tailings have long been considered as sinks or stocks, and Input-Output Analysis, which so far has essentially disregarded the environmental and resource burdens and benefits associated with tailings.

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