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LIFE CYCLE MANAGEMENT

Life Cycle Assessment in mineral processing – a review of the role of flotation

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Abstract

Purpose The aim of this literature review is to investigate the role of the beneficiation stage in the Life Cycle Assessment (LCA) of metals and minerals with a focus on the flotation process.

Methods The systematic literature search included LCA studies comprising the beneficiation stage in their system boundaries and resulted in 29 studies that met the criteria requirements and were analysed. First, the system boundaries are investigated, along with the level of detail in the description of the sub-processes (e.g. flotation) and data granularity. Then, the life cycle inventories are scrutinised: data transparency and the relation between system granularity and data availability is commented. Of particular relevance, the way in which the functional unit is dealt with is examined. Finally, studies impact assessments are compared and discussed, and key parameters are highlighted.

Results and discussion For system boundaries, beneficiation is generally embedded into the mining stage. Even when described on its own, important sub-processes (e.g. flotation) are not considered, except for eight cases analysed. Functional unit definition is hindered by the output of the system being an intermediate product. Indeed, most studies use a declared functional unit but fail to provide its relevant characteristics, which is essential for a correct interpretation of results and for comparisons. Most studies rely on secondary data, not always presented transparently, to describe beneficiation. Results on the role of beneficiation in the metal value chain environmental impacts are conflicting, partly because of its site dependency. Site-dependent parameters found to be determining are ore grade, energy mix, mining technique, concentrate grade and ore mineralogy.

Conclusions The flotation process, and more generally the beneficiation stage, is typically overlooked in LCA studies despite its growing relevance. Beneficiation not being assessed as a standalone stage, detailed in its subprocess, the use of outdated and secondary data, along with a lack of transparency in the inventory and in the key parameters are all factors that affect the environmental assessment of the entire metal and mineral sector, and thus the LCA of many products.

Recommendation Greater efforts should be allocated to considering the sub-processes in the beneficiation stage, particularly flotation. Information on the identified key parameters should be available to the practitioners and sensitivity analyses to investigate their influence are recommended. Hotspots specific to flotation have been identified and should be used to orient data gathering when focusing on this process. Five options of functional unit and their application are recommended.

Keywords Resources efficiency · Mineral processing · Metals · Flotation · Beneficiation · Life Cycle Assessment

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1 Introduction

Metals and minerals form the basis of Europe's economy. Their availability is becoming even more important nowadays, with the renewable transition and expanding digital sector (Mathieux et al. 2017). The use of secondary sources will not fully supply the increasing demand, at least in the foreseeable future. Extraction and concentration of primary materials will thus remain the main source of metals and minerals (European Commission 2018, Industrial Minerals Association – Europe 2018).

The production of primary metals includes ore mining, processing and refining to obtain the element in its metallic form. So far, the focus of Life Cycle Assessment (LCA) studies has been mainly on smelting and refining (Segura-Salazar et al. 2019). However, nowadays, as far as the demand is increasing and the supply is moving to lower grade deposits (Kutschke et al. 2015), the role of mining and beneficiation (the latter also known as mineral processing or ore dressing) is expected to become more and more relevant in terms of energy demand and environmental issues (Mudd and Jowitt 2018). Some studies have shown that mining and beneficiation can account for a significant contribution to the environmental impacts of the life cycle of metals (Davidson et al. 2016; Nuss and Eckelman 2014). Whilst these are very distinct stages, they have mostly been considered as just one stage in most LCA studies. This simplification makes it difficult to explore in greater detail the contribution of the specific processes to the various environmental indicators. Indeed, as discussed by Segura-Salazar et al. (2019), mining and beneficiation tend to be described as black-box models, in which the complex relationships between inputs and outputs are lost, thus preventing opportunities to identify the hotspots and enhance the overall environmental performance.

The beneficiation stage includes the separation/concentration processes required before further downstream processing in the refining stage. There is a variety of mineral separation methods available. Amongst those, froth flotation is the most important mineral separation technique (Shean and Cilliers 2011; Mesa and Brito-Parada 2019): for many metallic/mineral raw materials, processing without a flotation stage would be unthinkable (Rudolph 2018). By making use of differences in surface properties between minerals, valuable particles are concentrated in large tanks via their attachment to bubbles, which form a froth phase that overflows as a mineral-rich concentrate. In flotation, a wide range of chemical reagents are used to modify the surface properties of the valuable and gangue minerals and their separation response. Whilst flotation reagents are required to enhance recovery and grade of the concentrate, many of them incur in important environmental implications (Tao et al. 2019).

The aim of this literature review is to investigate the role of the beneficiation stage in the LCA of metals and minerals with a focus on the flotation process and its relevance to the overall system. This study is part of the FineFuture project (FineFuture 2020) whose aim is to develop new flotation technologies able to recover fine particles, which is currently a challenge for the processing of finely disseminated ores. Recovery efficiencies are low for very fine mineral particles, resulting in a significant part of valuable metals being lost to the tailings.

1.1 Paper structure

This review is structured in the following sections:

Methodology (Sect. 2): this section explains the literature search process, which papers have been selected and why.

Results (Sect. 3): in this section the selected papers are presented and classified according to the following concepts:

- Product system, system boundary and data availability

  The primary focus of the present paper was the flotation process. Thus, Sect. 3.1 deals with the system boundary and in particular with the level of detail in the description of the subsystems and data granularity in the mining sector. This directly leads to the topic of data availability and life cycle inventory (LCI) since most of the time system granularity reflects data availability.
- Functional unit and multi-functionality

  Deeply related to the system boundary and to the comparability amongst studies is the functional unit and the way multi-functionalities are solved. These aspects are analysed in Sects. 3.2 and 3.3.
- Impact assessment and interpretation

  Outstanding impact categories and their limitations when applied to the mining sector with emphasis on the beneficiation and flotation are presented in Sect. 3.4. Identification of the hotspots of the mining sector in general and of the beneficiation stage and flotation process in particular is discussed in Sect. 3.5. Key parameters influencing the results and sensitivity analysis are listed in Sect. 3.6.

Discussion (Sect. 4): in this section trends and limitations found in the literature and presented in the result section are discussed, following the same structure as Sect. 3, and recommendations are presented.

Conclusions and recommendations (Sect. 5): main trends found in Sect. 3 are summarised and the key points of discussion section are recalled, along with the recommendation for future studies in the sector.

Table 1 Search strings listed in order of decreasing criteria stringency and results

Research string	Engine results	Pertinent results	Available pertinent results
LCA + flotation	1	1	1
LCA + concentrate	53	4	2
LCA + beneficiation	62	17	12
LCA + metal/mineral	57	30	14 *(of which 3 reviews)*

2 Methodology

The focus of the study is the role of the beneficiation in the production of metals and minerals in terms of environmental impacts, with a focus on the flotation process. The literature search included LCA studies comprising the beneficiation stage in their system boundaries, both for mineral and metal processing.

The literature search was performed on Scopus, Web of Science and OneMine. The following keywords and synonyms were considered:

- LCA and life cycle assessment, life cycle analysis, environmental impact, environmental assessment, impact assessment;
- Flotation;
- Concentration (as flotation is a type of concentration method) and the resulting product of this process, the concentrate;
- Beneficiation (as the flotation process is part of it) and its synonyms mineral processing, ore dressing;
- Metal sector and mining sector.

Table 1 reports the search strings and the final number of selected studies. A first screening was based on the title and the abstract, to exclude nonpertinent studies. A consistent part of the search results was misleading because of multisemantic terms, such as beneficiation and concentration, used in the search string. A second screen was based on the actual availability of the shortlist of papers. Abstracts published in conference proceedings not available to the public were excluded. Papers available via standard academic subscriptions were included. The sources are scientific papers, industrial reports and datasets from the most common databases.

Figure 1 describes the selected studies and the way we structured our search: only one study focused on the flotation process itself (Broadhurst et al. 2015) and it applied to tailing management. Thus, the search opened up in concentric circles moving from the unit process (flotation) to the subsystem (beneficiation) to the complete LCA of metals and minerals, to understand how beneficiation has been treated in the studies.

The journal papers and conference proceedings selected for the revisions are 29. For the complete list, the reader is referred to the Appendix.

3 Results

In the following section, the revised papers are presented and described following the structure of an LCA.

3.1 Product system, system boundary and data availability

The type of papers reported in Table 1 show that the flotation process has not been investigated as a stand-alone topic; it rather appears mentioned in specific LCAs of material production. Figure 2 represents the main stream of each system boundary and the level of detail used to describe the beneficiation stage in the reviewed papers. Far from being an exhaustive representation of mining and metal LCAs in the

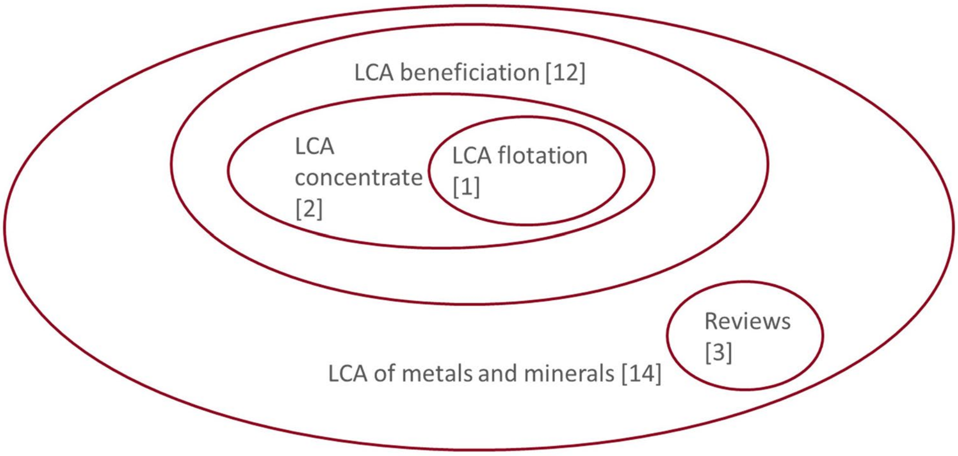

Fig. 1 Synoptic view of the research path, moving from the most stringent string search focusing on flotation to the wider one, including studies of the entire metal and mineral value chains. The number of available results for each string is given in brackets

Fig. 2 Representation of the main stream of the system boundary of the reviewed paper

literature, this representation was aimed at depicting how the studies that presented higher attention to the mining and processing stages represented the latter, and especially with which level of detail, both in the description of the subprocesses, and in the sources of data. In the following paragraphs we are presenting the reviewed papers grouped on the basis of the level of detail they describe the beneficiation stage.

3.1.1 Group 1 – mining and beneficiation as a single stage

Most of the studies considered beneficiation altogether with the mining operation. For example, Awuah-Offei and Adekpedjou (2011) carried out a review scrutinising the very first LCAs applied to the mining sector. This work is focused on the extraction stage, and it mentions the beneficiation stage only when it is included in the articles reviewed: this happens when the beneficiation occurs at the same place as the mining activities. According to them, one of the main limitations regarding the data availability and the system granularity was the representation of the mining stage as a black box. Farjana et al. (2019a) reviewed 38 research articles, covering 16 metal industries, ranging from mining to refining, looking for the key processes of the mining sector. The beneficiation is mentioned as part of the mining stage (as opposed to the downstream smelting and refining processes), reflecting the way system boundaries are structured in the literature analysed. The same happens in Memary et al. (2012) and Hong et al. (2018). In the pyrometallurgical process to produce cathode copper analysed in Li et al. (2017), mining and beneficiation are considered as a single process, whose modelling is based on secondary data derived from the Yearbook of Nonferrous Metals Industry of China. Wang et al. (2015) combined different databases (ecoinvent, sinocentre database, report from China Nonferrous metal industry association) to perform cradle to gate LCA of the refined copper production in China: beneficiation steps are not mentioned; they are most likely included in the mining stage.

Farjana et al. (2019b) analysed the datasets on manganese beneficiation and refining from ecoinvent and AusLCI. Their analysis is a cradle to gate LCA, where the extraction and mining operation are considered as subprocesses of the beneficiation stage (note this is not in agreement with the accepted definition of beneficiation). The final product is high-grade manganese (the grade is not specified). Farjana et al. (2019c) analysed the co-production of copper, gold, lead, silver and zinc. As in Farjana et al. (2019b), the extraction and mining

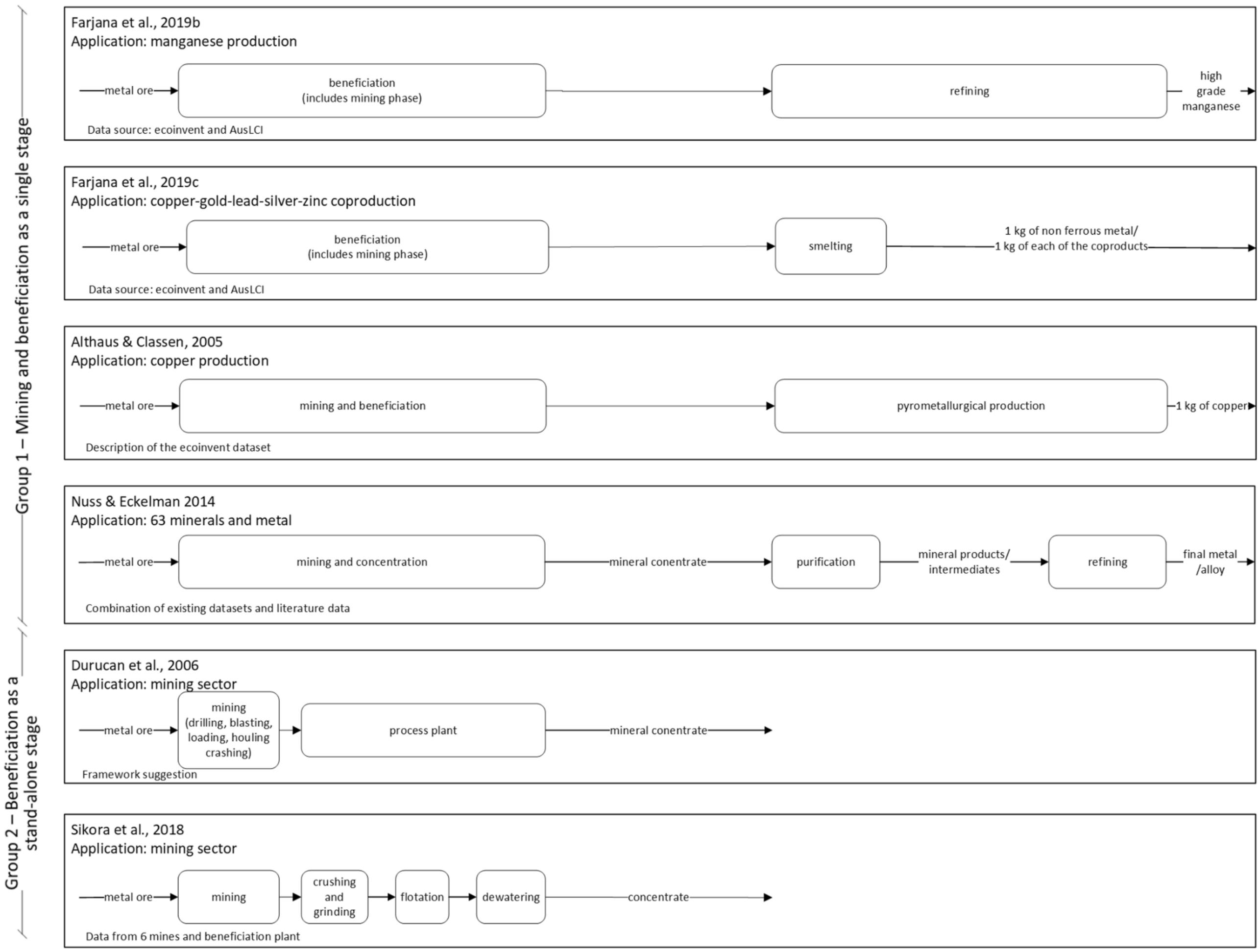

Fig. 2 (continued)

operation are considered as subprocesses of the beneficiation stage.

Althaus and Classen (2005) presented the goal and scope of metal inventories in the ecoinvent database. As a case study, they presented the primary copper production. Mining and beneficiation are grouped in a single stage. Nuss and Eckelman (2014) combined existing datasets and literature data for 63 metals, grouping mining and beneficiation in a single stage.

3.1.2 Group 2 – beneficiation as a stand-alone stage

Some papers take the beneficiation stage separate from the mining activities in the system boundary but still present some limitations when the data availability (i.e. the inventory) is considered. For example, Durucan et al. (2006) proposed a model able to represent a mining system in a comprehensive way: their model integrates the mine production, processing, waste treatment and disposal, rehabilitation and aftercare stages of a mine life. However, whilst a detailed subsection in the tool is dedicated to operations regarding excavation, for the beneficiation the level of details stops at “mineral processing”. The paper by Sikora et al. (2018) details the process of beneficiation in its subprocesses (namely crushing and grinding, flotation and dewatering). However, they did not detail the inventory in the same way. Inventory data was sourced from published papers, sustainability reports by mining companies, independent technical reports and previous studies performed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Van Genderen et al. (2016) assessed the global life cycle of zinc production, with the system boundary spanning from mining to processing. The beneficiation stage considered comminution and flotation. Even though no specific data for the flotation are provided, at least mineral processing is considered as a separate unit process from mining. Westfall et al. (2016) provided an assessment of the manganese global industry, performing LCA of the most common manganese products and using primary data from 16 ore and alloy producers worldwide. The system boundary includes

Fig. 2 (continued)

mining, processing/beneficiation, sintering and smelting. However, in Sect. 3 of the paper, impacts from mining, processing and sintering are grouped into a single entry. In the cradle to gate LCA study by Norgate and Rankin (2000), the pyrometallurgical route for the production of refined copper and refined nickel includes a beneficiation stage: the inventory consists of literature data and it is limited to few flows, but it is transparent and every flow is detailed, with amount, references and contributions to each unit process.

3.1.3 Group 3 – beneficiation detailed in its subprocesses/detailed at the level of flotation

Finally, some papers take the beneficiation stage separate from the mining activities both in the system boundary and in the inventory. In the case study of an underground copper mine by Song et al. (2017), the mining process includes drilling, blasting, loading and hauling and primary crushing. The beneficiation (i.e. mineral processing) is well detailed at the level of the unit process and data are provided by the owner: after the mining operation the mineral passes through a semi-autogenous mill and then a secondary mill, after which it enters the froth flotation tanks and cleaners, the thickener and the filter. Li et al. (2008) compared the concentration process of copper ore and copper slag. The stages included are concentration (crushing, milling, flotation) and smelting (conversion and refining). The final product is cathode copper. The data are both from a company and the literature, but no further details are provided. Song et al. (2014), who analysed the production of copper in China by using data from two plants, considered beneficiation as an individual stage, split from mining. Northey et al. (2014) assessed the water footprint of copper, gold and nickel production in Australia, based on literature data. System boundary of pyrometallurgical production of copper sulphide and nickel sulphide and processing of gold refractory ore are well detailed for the mineral processing, and in the Life Cycle Inventory (LCI) the same granularity as the system boundary was used. Milling, flotation and thickening have a dedicated unit process each. Flotation finds applications

Fig. 2 (continued)

also in precious and rare metal beneficiation. Evidence of its relevance can be found in LCA studies on platinum group metals (PGM) (Mabiza et al. 2014) and on rare earth elements (REEs) (Pell et al. 2019; Canino et al. 2005) along with LCA studies on REE recoveries from tailings of other metals (Grzesik et al. 2019). In Mabiza et al. (2014) the production process is well detailed via a flow chart and a mass balance of material flows, and the system boundary ranges from the extraction to the gate of the concentration plant. Pell et al. (2019) sought to demonstrate the capability of LCA to provide information and address project developments also in the early stage of a project, performed a process simulation-based LCA of REE extraction and processing plant for a potential new supply in Malawi. Different project options are examined. In the present review we will discuss only the one that resulted to be the best performing scenario, since it is the one for which a detailed process contribution analysis has been performed. The system boundary details the mineral processing stage into the following unit processes: crushing and milling, flotation, leaching and dissolution and precipitation. Data have been derived from a prefeasibility flowsheet from Mkango Resource Ltd, literature, simulation with HSC Chemistry software and ecoinvent and GaBi databases. Canino et al. (2005) analysed the mining and processing of lanthanides from bastnaesite ores, considering the technology used in the Mountain Pass mine in California (USA) where lanthanide concentration is done through flotation. The study is a cradle to gate inventory and data were gathered from available database and literature data from Mountain Pass mine and other worldwide mining and processing sites.

Shifting the focus to other material analysis (i.e. silica sand by Grbeš (2016)) or to other sources (i.e. secondary sources like tailings, analysed by Broadhurst et al. (2015) and by Grzesik et al. (2019)) (Fig. 3), it is possible to find a deeper level of detail on the beneficiation stage. Grbeš (2016) compared three different beneficiation routes for silica sand concentration (electrostatic separation, flotation, gravity concentration): the beneficiation is detailed in every subprocess and described with primary data gathered at open pit mines of silica sand in Croatia. Grzesik et al. (2019) presented a focus on the beneficiation of tailings in order

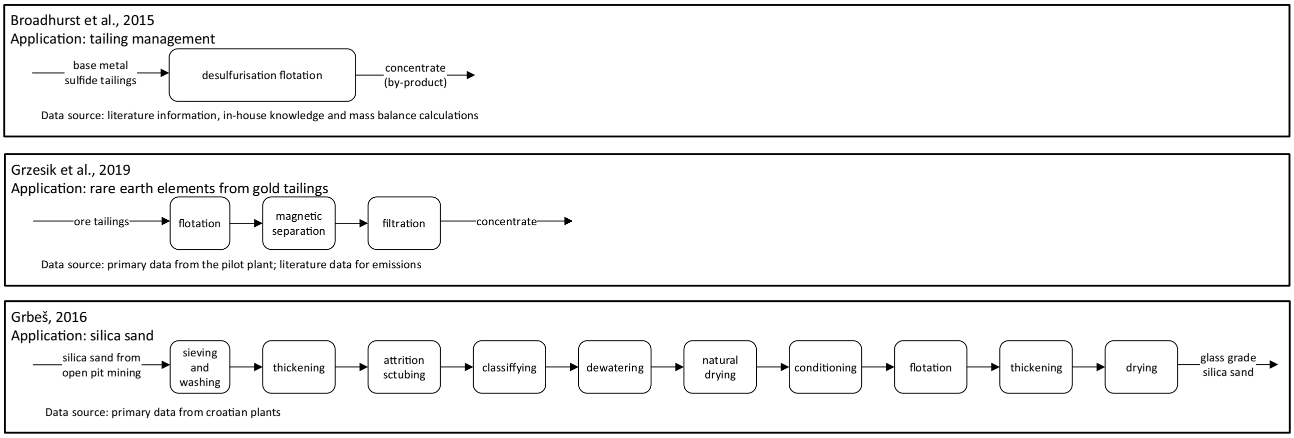

Fig. 3 Representation of the main stream of the system boundary of the papers analysed to complement the analysis

to recover REEs. The system is detailed at the unit process level and the LCA is based on primary data from the pilot plant. When tailings undergo a flotation step, the system boundary includes their transportation from the mine to the REE processing facility, the beneficiation – which is subdivided into flotation, magnetic separation and filtration – and then waste deposition and land reclamation. The paper by Broadhurst et al. is the only study primarily addressing the flotation process (Broadhurst et al. 2015). In their analysis, they evaluated the impacts of desulphurisation of base metal sulphide tailings, via froth flotation, to reduce acid rock drainage (ARD) and at the same time to obtain valuable by-products. Their assessment is thus focused on the tailings, and the system boundary includes the treatment of the tailings, not the upstream processes of the metal. Inventory background data are from ecoinvent for the electricity production, and from Kunene (2015) for the reagent production. Data for the foreground system were derived by a combination of literature information, in-house knowledge and mass balance calculation.

3.2 Functional unit

The functional unit is a quantified measure of the performance of the functional outputs of the product system (International Organization for Standardization [ISO] 14044, 2006). It answers the questions what, how much, how well and for how long the object of the study performs the function (Del Duce et al. 2013). The definition of a functional unit is of utmost importance to guarantee a fair comparison amongst alternative products. A precondition of a comparative LCA is the equality of the function of the compared systems. This has to be considered by formulating the functional unit, i.e. the reference quantity of comparison (Fleischer and Schmidt 1996).

However, when limiting the analysis to a cradle to gate, the fulfilment of the function of the product/service happens outside the system boundary, in a space and a time the practitioner has no access to. Moreover, if for a final product it is easier to identify the function, assuming a certain use fate, the function of an intermediate product – such as the concentrate – is more difficult to be identified.

Amongst the studies presented and described in Sect. 3.1, in this section we are analysing only studies that limited their system boundaries up to the beneficiation/concentration stage and presenting how they addressed the issue of the functional unit.

The origin of the differences in the studies revised by Awuah-Offei and Adekpedjou (2011) is mainly based on the difference in the system boundary and in the functional unit. The functional unit is typically the production of the product and the reference flow the unit (1 kg, 1 piece) of product, but they suggest that a relevant reference flow might be also the rate of production (Awuah-Offei et al. 2009).

In the years following the work by Awuah-Offei and collaborators, all the studies (with two exceptions) have identified the functional unit in the production of the product that leaves the gate of the system boundary, i.e. the concentrate. However, this makes these studies more appropriate for internal purposes, limiting information extrapolation. Especially because a relatively small group has provided information about the concentrate quality and its characteristics, which will eventually allow further normalisation on the basis of these characteristics, for example the amount of valuable metal contained in the concentrate (i.e. the concentrate grade). The lack of this information prevents use of the studies for downstream impact calculation. Notably, there is always a trade-off between metal recovery in the concentrate and concentrate grade, and this directly impacts on smelter contracts, which will pay for the metal but charge for the tonnage treated and will also penalise impurities. This trade-off is also highly impacted by metal prices and so the concentration of metal in the concentrate becomes a parameter that needs to be continuously assessed.

The functional units mentioned so far are closer to declared units: a declared unit is used instead of a functional unit when the precise function of the product is not stated or known, or when the LCA does not cover a full life cycle. If a declared unit is used, all the relevant characteristics of the product should be clearly mentioned, in order to allow a correct use of the result of the analysis to whom will use them in a complete LCA. However, this was not the case of the revised studies that use the production of product as the functional unit and the unit of product as the reference flow. In these studies, the concentrate is not accompanied with detailed description and only Sikora et al. (2018) mentioned the concentrate grade.

Following the idea that the first function of a concentrate production should be to provide a certain amount of valuable metal to the downstream smelters/refiners, two studies have considered the amount of valuable metal as the functional unit: Farjana et al. (2019c) and Song et al. (2017). Song et al. (2017) stated that using the amount of copper is the only way "to ensure a fair comparison between the life cycle impacts of this mine and other copper ore mine operations on varying grades of ore and/or concentrate". They are also the only ones, to the authors' best knowledge, to mention additional characteristics of the concentrate and its comparability amongst different systems. In their study they analysed the traditional copper concentration process with another scenario, where tailings are also treated via electrodialytic treatment before disposal, to recover additional valuable materials. In both cases the reference flow is 1 kg of copper in the concentrate (45% concentration), which also contains 1.27 g of silver and 0.01 g of gold. In the scenario with the recovery of material from tailings, the reference flow becomes 1 kg of copper as a sum of copper in concentrate and copper recovered from tailings.

3.3 Multi-functionality

Multi-functionality is often key in the LCA of metal production, in a context where metals are often co-produced. In Table 2, the studies that faced multi-functionalities are collected and classified based on the solving method.

Eleven studies mention the presence of co-products in the production route. The study by Sikora et al. mentions the allocation method but not the co-products, whereas Canino et al. (2005) refer to co-products but not to the allocation method. In the case of Pell et al. (2019) and Mabiza et al. (2014), the functional unit is the concentrate containing a mix of valuable metals: there is not a primary product in the concentrate; they are considered all co-products and impacts allocated. Few studies specify the form of the co-products and at what stage they are generated. Some studies only mention the elements; the majority only specify the form (concentrate or refined). Only Song et al. (2017) provides other characteristics, such as the amount of valuable metals in the concentrate. Besides the studies listed in Table 2, three studies specify that their product systems are single-output production routes, and thus, no co-products are present and no allocation methods are required (Farjana et al. 2019b; Northey et al. 2014; Westfall et al. 2016). The remaining studies analysed in this review do not acknowledge the issue of co-products and multi-functionality.

3.4 Selection of impact categories

The selection of the impact categories is not always straightforward when it comes to the metal and mineral sector. Various studies normalised the results and obtained different Areas of Protection (AoP) priorities. According to Song et al. (2017) these differences are linked to the very site-specific reality of mining activities. They also implicitly suggested that local issues might also address the choice of the impact categories to be considered. Santero and Hendry (2016), in their pursuit of an LCA harmonisation in the metal and mining sector, recommended to consider the following impact categories: Cumulative Energy Demand (CED), global warming, acidification, eutrophication, smog potential and ozone depletion. At the same time, they stressed the importance of accounting for water consumption and waste generation. Awuah-Offei and Adekpedjou (2011) in their review acknowledged the importance of properly investigating impact categories like resource depletion, land use, CED and water depletion, besides usual impact categories. The assessment of abiotic resource depletion poses a problem because of the method to account for it. There are plenty of methods for assessing abiotic depletion, reflecting different concepts (Sonderegger et al. 2020). Comparing all these methods is beyond the aim of this paper, whilst it has been addressed in recent works in this field: Klinglmair et al. (2014), Berger et al. (2020) and Alvarenga et al. (2016).

Land use is also a relevant area of protection in the mining and beneficiation sector, because of the long period of exclusive use. It is addressed both as land occupation and land transformation. In the beneficiation stage, a relevant part of it is linked to tailing management and tailing ponds. This impact category has been addressed by studies focusing on flotation tailings (Broadhurst et al. 2015; Grzesik et al. 2019). The recovery of metals from tailings does not significantly decrease land occupation, because of the low concentration of metals in the tailings. However, reprocessing can play a role in reducing the environmental risks posed by tailing storage facilities, as discussed by Edraki et al. (2014), whilst Reid et al. (2009) found that the land use is a very

Table 2 Multi-functionalities in the literature

Study	Main product	Co-products	Method to solve multi-functionality
Althaus and Classen (2005)	Copper concentrate	Molybdenite concentrate. Extracted from sulphidic ore and separated at the beneficiation stage	Allocation by mass (for the coupled resources, so to respect mass conservation) and by economic revenue for the other exchanges
Northey et al. (2013)	Copper matte, blister copper, fire-refined copper anode	Au, Mo, Zn, Ag, U, Pb (not known the state of the co-products)	Economic allocation
Song et al. (2017)	Copper concentrate	Silver and gold concentrate	Economic allocation
Van Genderen et al. (2016)	Zinc concentrate, refined zinc	Co-products in mining and beneficiation of zinc: copper, lead and zinc concentrates, agricultural lime. Co-products in smelting: special high-grade Zn, Cu cement, Cd, Co cement, Mn sludge, Zn alloys, Zn dross, Al dross, sulphuric acid	Physical allocation. Sensitivity analysis on allocation method: total mass versus mass of metal content. System expansion for sulfuric acid
Pell et al. (2019)	A mixed REO (Rare Earth Oxides) concentrate	Lanthanium, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, dysprosium, yttium, holmium, erbium, thulium, ytterbium, lutetium (in concentrate)	Mass and economic allocation
Mabiza et al. (2014)	Platinum group metal (PGM) concentrate	"Useful PGM metals"	Avoided using the input ore as functional unit
Memary et al. (2012)	Copper concentrate, refined copper	"Mainly gold and silver"	Surplus method (not explicit)
Sikora et al. (2018)	Copper concentrate	Not specified	Mass-based allocation
Canino et al. (2005)	(La,Ln)Cl3	CaF2	Not mentioned/not applied
Farjana et al. (2019c)	Sintered copper, gold, lead, silver and zinc	Sintered copper, gold, lead, silver and zinc	Revenue-based allocation
Nuss and Eckelman (2014)	63 refined metals/alloys	Co-products at the concentration and at the refining stages	Sensitivity analysis of mass and economic allocation A 5-year price average is used to control for price volatility
Norgate and Haque (2012)	Refined gold	Refined silver	Economic (gold/silver ratio 45) and mass allocation

important contributor to the overall environmental impact assessment of tailing management strategies.

Hong et al. (2018), in their comparative LCA of refined copper from primary and secondary sources, obtained for the former an outstanding role in marine ecotoxicity and freshwater ecotoxicity, land occupation and water depletion. Li et al. (2008), however, reported similar impacts from primary and secondary copper sources.

3.5 Impact assessment

The review of Life Cycle Impact Assessment (LCIA) in the literature presented hereafter focuses on flotation. Since there are no studies focusing on the flotation process itself, studies performing a process contribution which includes impacts pertaining to flotation are discussed in this paragraph and summarised in Table 3, along with the impact categories for which the process contribution is performed and the results they get. Table 4 summarised instead the results of the impact assessment for those studies where the whole beneficiation is analysed (and not the flotation as a stand-alone process).

Looking at Table 3 and Table 4, it appears difficult to give a final judgement about the contribution of flotation to the total impacts for two main reasons. First, in some cases (those reported in Table 4) flotation is not taken separately and this prevents a detailed interpretation of the results. Second, even where the flotation is considered as a stand-alone unit (Table 3), the differences in the system boundary in the analysed studies make it very difficult (if not impossible) to quantify for each impact category an average value representative of the contribution of the flotation.

Table 3 Results performing process contribution on flotation

Reference	Product system	Impact categories	Flotation impacts	Out of how many unit processes
Pell et al. (2019)	Rare Earth Oxide concentrate	Acidification, ecotoxicity, eutrophication, global warming, particulate air, human toxicity (cancer), human toxicity (non-cancer), smog air (TRACI 2.1)	Below 20% everywhere (main contribution: acidification and smog air around 15%) In global warming, where it represents around 5% and 70% is connected to reagents production, 12% electricity and the rest water	Mining, crushing and milling flotation, leach and dissolution, precipitation, acid regeneration waste management
Norgate and Haque (2012)	Refined gold from non-refractory ore	GHG	Less than 5%	Mining, comminution, flotation, cyanidation, CIP, EW, smelting, other, chlorination, electrolytic process, silver refining
Northey and Haque (2013)	Refined copper, gold and nickel (single-output routes, no joint production)	Direct and indirect water consumption	Milling and flotation representing the main invoice of direct use for the three metals	Mine, milling and flotation, smelter and acid plant, refinery
Canino et al. (2005)	Lanthanide chloride concentrate production from bastnaesite	Energy consumption, water consumption (inventory aggregation, no assessment method used)	60% of total energy consumption, 90% of total water consumption	Mining, milling, flotation

Table 4 Results performing process contribution on beneficiation

Reference	Product system	Impact categories	Beneficiation impacts	Out of how many unit processes
Norgate and Rankin (2000)	Refined nickel and copper	Climate change	Second most impacting phase, mainly because of energy intensity of the process	Mining, mineral processing, smelting refining, mining, crushing, leach (flotation reagents excluded)
Farjana et al. (2019b)	Refined manganese	15 ILCD midpoint categories	Predominance of beneficiation in all the categories	Beneficiation, refining
Song et al. (2014)	Cathode copper	Ecopoint	33% of total burden	Mining, transportation, beneficiation, dewatering, flash smelting, converting, fire refining, electrolytic refining
Nuss and Eckelman (2014)	63 refined metals and minerals	Cumulative energy demand Climate change Human health Ecosystem damage	Predominance of mining and beneficiation for Cu and Mn; for all the other metals, refining stages are more relevant	Mining/concentration, purification, refining
Memary et al. (2012)	Refined copper	Climate change	Mining and milling account for 57% of total climate change impact	Mining and milling, smelting, gas treatment, electrorefining, converting, slag cleaning

3.6 Key parameters

In this section key parameters identified in the literature for what concerns impacts of the beneficiation stage are reported. Those aspects are related to the beneficiation stage in general; in Sect. 4.5 the effects these key parameters can have on the flotation process in particular are discussed.

Table 5 reports the key parameters acknowledged by authors in the scientific literature. It also mentions if any sensitivity analysis or correlation curve has been performed in the studies.

Five key parameters have been identified by the authors of the reviewed studies, i.e. ore grade, energy mix, ore mineralogy, production scale and allocation method.

Ore grade is a parameter acknowledged as a determining factor in the impacts of mineral processing by many authors. It directly affects waste generation, water consumption (Northey et al. 2014) and energy demand (Calvo et al. 2016; Memary et al. 2012).

Besides ore grade, ore mineralogy has been found to affect the concentration process and its impacts. Its role is visible at many levels. Ore hardness is a major determinant in electricity use for grinding (Sikora et al. 2018). It also directly affects beneficiation, and flotation in particular, since variance in ore mineralogy largely influences the concentrate grade (and extractable metal). It also determines the quantity of reagents required. This aspect has effects downstream because it affects transfer of metals in tailings (Althaus and Classen 2005). Sikora et al. scaled the results from six different copper concentration plants to a common concentration grade; they obtained no clear relationship between energy and reagent consumption explaining the remaining differences due to variance in ore mineralogy.

The energy mix is a determining aspect in every energy intensive process (Marmiroli et al. 2018) Aware of that, Sikora et al. (2018) normalised the results of the different concentration plants to a common fictional electricity mix, sourced only by natural gas.

Production scale was found to be an influencing parameter for concentrate production. Northey et al. (2013) found a correlation between copper concentrate tonnage and water consumption.

Allocation method is a relevant parameter when it comes to determine impacts of products, especially in a sector like mineral processing, where joint production is the norm. Effects of this parameter are discussed in Sect. 4.4.

Table 5 Key parameters and sensitivity analyses performed in the literature

Key parameter	Analysis performed
Ore grade	Correlation curve ore grade — energy consumption (Norgate and Rankin 2000) Correlation curve ore grade — energy consumption (Sikora et al. 2018) Correlation curves between ore grade and GHG emissions (Norgate and Rankin 2000) Correlation curve ore grade — water consumption (Norgate and Lovel 2006) Correlation curve ore grade-water type of ore (refractory vs. non refractory ore) (Northey and Haque 2013) Linear scaling on concentrate grade (Sikora et al. 2018)
Energy mix	Sensitivity analysis (Farjana et al. 2019c) Linear scaling on electricity source (Sikora et al. 2018)
Ore mineralogy	Correlation curve ore grade-water type of ore (refractory vs. non refractory ore) (Northey and Haque 2013)
Production scale	Correlation curve water consumption —— copper concentrate production (Northey et al. 2013)
Allocation method	Sensitivity analysis of mass and economic allocation (Nuss and Eckelman 2014) Sensitivity analysis on allocation method: total mass versus mass of metal content (Van Genderen et al. 2016)

4 Discussion

In this section, trends in the results presented above are identified and discussed following the same structure as Sect. 3. Also, a tentative answer is proposed to the reason as to why the flotation process, and more generally the entire beneficiation stage, is overlooked in LCA studies. Limiting the analysis to this stage encounters some difficulties, in our view mainly since the analysis is limited to an intermediate product (from an LCA perspective). This leads to some hurdles mainly in the definition of the functional unit. Thus, possible options are proposed and sifted through in Sect. 4.3.

4.1 Product system and system boundary

The type of papers reported in Table 1 shows that the flotation process has not been investigated as a stand-alone topic; it rather appears mentioned in LCAs of the entire production process of minerals and metals. As a result, no established knowledge on the flotation process itself is available from an LCA point of view. Even the beneficiation stage does not appear to be the focus of any but few studies. It is rarely detailed in its unit processes, it is sometimes grouped with the mining stage, and in other cases, it is not even mentioned. Amongst the reasons as to why beneficiation and mining are grouped together in many studies, they happen at the same site; thus, data collected are often aggregated by the provider. The prevailing system boundary in LCA of the mineral and mining sector is the cradle-to-gate. The underlying concept of this selection is that, having the producers no influence on the downstream use, they can however provide the LCA community the necessary data for external, cradle-to-grave studies performed by other practitioners. In these circumstances, cradle-to-gate studies still provide important details about the potential environmental impacts but should be used with caution and should not be compared unless functional equivalency has been established at the level of the finished product (Santero and Hendry 2016). It is also regarded as a valid way for comparing different systems producing the same product or service, whenever their downstream stages are the same (Norgate and Rankin 2000). To summarise, the analysis of the system boundary in the literature shows that the beneficiation processes are mostly overlooked:

- The beneficiation stage is most of the time embedded in the mining stage;
- Whenever it is described in the system boundary with a dedicated unit, it is not detailed in sub processes (e.g. flotation), except for eight cases;
- It is mostly modelled with secondary data.

The latter is a point that affects the entire metal sector, and finally the LCA of many products, given that the production of materials is crucial in many other product chains. This is even more surprising considering the general awareness of the role of the beneficiation stage and its growing importance over time due to lower grade deposits. Due to the general reliance on literature data for modelling this stage (Segura-Salazar et al. 2019), there is scope to enhance LCA studies in this area by addressing the beneficiation stage with primary data, to increase the level of detail of the LCI and evaluate the effects of a more detailed LCI on the results (Marmiroli et al. 2020).

4.2 Data availability

Data availability and transparency in publishing them in LCA reports influence every aspect of LCA layout. The state of the art in LCA of mineral processing shows the predominance of literature data (only eight studies rely on primary data for the foreground processes; see Fig. 2), and aggregated data (mining and beneficiation modelled as a single unit and when split they are rarely detailed in subprocesses). As seen in Sect. 4.1, the aggregation level of data determines the system boundary and influences the way the flow chart is structured. This reflects on Life Cycle Impact Assessment (LCIA), limiting the analysis of process contribution, since aggregated data can only convey aggregated results. It also limits performing sensitivity analysis and limits the scientific community in drawing trends amongst the results of the studies, because not characterised with enough information.

It also influences the selection of the impact categories to be analysed: Santero and Hendry (2016) define which impact categories are recommended also on the basis of how reliable are LCI data that contributes to those categories.

In such a site-specific production, transparency is functional for the reproducibility of the study. Moreover, having detailed information on product characteristics and ore is the only way to perform extrapolations, define trends amongst key aspects and draw useful information and good practices for the industry; otherwise, it remains a report for internal purpose.

As a conclusion, the LCA community needs more primary data, less aggregated and presented in a more transparent way, not only for what concern inventory of energy and materials, but also data characterising products and co-products. Also, data regarding key parameters (presented in Sect. 4.6) should be provided.

4.3 Functional unit

Adequately selecting a functional unit is of prime importance because different functional units could lead to different results for the same product systems (Reap et al. 2008a, b). The flotation concentrate is an intermediate product in the metal value chain, which makes its function definition not straightforward. Relevant characteristics for concentrate are manifold; they include concentrate grade, granulometry, other valuable metals or penalty elements contained in it and many other characteristics depending on the ore mineralogy. Thus, defining its function for comparative purposes is not so easy.

In order to solve this problem, we discuss five options of functional unit and their application for studies that want to focus on the beneficiation stage, and particularly including the flotation process (Table 6).

1. The final product

   Following the suggestion by Del Duce, “if some of the relevant aspects of the products to be compared are not identical, the systems have to be expanded to the point where equivalent functionality is achieved” (Del Duce et al. 2013). In the case of the minerals and metal sector, that would require extending the analysis to the final product. In this sector, the expansion will also include the refining processes, to the refined metal. This solution, theoretically the most adequate, is also the least feasible if our aim is to foster mining and metal sector LCA based on primary data. In fact, as mentioned by Norgate and Rankin (2000), an LCA practitioner usually does not have full control of what happens downstream. The practitioner usually has primary data only on a part of the product life cycle. Requesting practitioners to perform complete LCAs might be time demanding and

Table 6 Function of the system and possible functional units (FUs). The reference flow is indicated too

Type of functional unit	Function of the system	Functional unit	Reference flow	Results (example with climate change)
Final product	The primary function of the system is to produce a product to be sold on the market	The FU is the production of a certain amount (e.g. 1 tonne) of refined metal	1 tonne of refined metal	$\frac{kg\ of\ CO_2 eq.}{1\ tonne\ refined\ metal}$
Intermediate product	The primary function of the system is to produce a product to be sold on the market	The FU is the production of a certain amount (e.g. 1 tonne) of concentrate at the plant	1 tonne of concentrate produced	$\frac{kg\ CO_2\ eq.}{1\ tonne\ concentrate}$
Metal content in the product	The primary function of the system is to produce a product to be sold on the market	The FU is the production of a certain amount of metal (e.g. 1 tonne) in the concentrate	Amount of concentrate containing 1 tonne of metal	$\frac{kg\ of\ CO_2 eq.}{1\ tonne\ metal\ in\ the\ concentrate}$
Input based	The primary function of the system is the management of the input (tailings or primary ores)	The FU is the processing of a certain amount (e.g. 1 tonne) of ore at the plant	1 tonne of input ore	$\frac{kg\ of\ CO_2 \mathrm{eq.}}{1\ tonne\ of\ input\ ore}$
Normalised on the input	The primary function of the system is the optimization of the metal recovery in the flotation process	The FU is a certain recovery efficiency	% of recovery efficiency	$\frac{kg\ of\ CO_2 eq.}{\%\ of\ recovery}$

leave the community without detailed LCAs on mining and beneficiation.

The problem could be solved setting as a foreground the mining and beneficiation, whilst considering the downstream processes in the background. However, so far, the level of detail in the mining and beneficiation sector has been low, and no attention has been given as to how the characteristics of the concentrate will affect the downstream processes. This further complicates the issue, since secondary data from the literature are not able to be adjusted depending on the characteristics of the concentrate. The result would be a downstream stage (smelting and refining) modelled in the same way regardless of the concentrate, which is useless for this kind of analysis.

2. The intermediate product

   In this option, the functional unit is the production of the concentrate. This represents more a declared unit rather than a functional unit because it does not reflect the function that the product will fulfil downstream. However, it can be useful for internal purposes, to preliminary identify hotspots in the production chain, highlight relevant parameters and support eco-design. It could be used for comparative purposes, only for concentrates sharing the same characteristics (which is a rare situation in real life due to the very site-specific nature of every concentrate).

3. The content of valuable metal (i.e. the commodity oriented functional unit)

   Weidema (2017) suggested that to define the functional unit, the so-called obligatory properties of the product (i.e. those properties that a functional unit must have in order to be considered as a relevant alternative (Weidema et al. 2004)) need to be identified. Thus, we asked a few producers (a representative of copper concentrate, a representative of manganese and two representatives for magnesite) to identify them in the market segment they operate. Regardless of the application, the first property was the content of valuable mineral or metal. Following this consideration, the use of a functional unit based on the content of valuable metal in the product seems the most adequate. This functional unit reflects the idea that the function of the concentrate is to provide valuable metals to the downstream stages, for the metals to be processed. It quantifies the function of the system, i.e. the recovery of the metal and represents the real function of the concentrate, the one that determines the market segment.

   However, there is an aspect that is being neglected by both the papers (Farjana et al. 2019c; Song et al. 2017) that used this functional unit: the characteristic of the reference flow. The reference flow is the mass of product that provides the functional unit; in the two aforementioned cases, it is the mass of copper concentrate containing 1 kg of copper metal. Even if the functional unit is the valuable metal, the amount and the characteristics of the concentrate containing the metal will also affect the phases downstream. Just to mention some of them, the mass of the concentrate will affect impacts from transportation, and the concentrate grade will affect the intensity of the refining processes and its emissions. Another aspect to keep in mind is that other relevant characteristics of the concentrate might hinder the functional equivalence of the selected functional unit (e.g. granulometry, amount of other metals).

4. The input-based functional unit

   The functional unit can also be defined considering a flow entering the system rather than a product leaving it. This is the case of systems whose primary function is to dispose wastes. In the case of raw materials, this functional unit has been used in all the studies and projects analysing recovery of materials from mining waste and tailings. Broadhurst et al. (2015) set the "reference flowrate of 100 tonnes of dry tailings per day", with the recovered metals being the co-product of the system. Grzesik's functional unit is "defined as 1000 kg of a secondary source, to be excavated and processed, as the input for all subsequent processes of REE recovery" (Grzesik et al. 2019). This functional unit eases most of the problems related to the properties of the concentrate, moving the attention to the function of managing the material entering the system. However, this functional unit can be used only in circumstances where the primary function is the disposal of materials, which is not the case for most beneficiation plants. Furthermore, this functional unit creates a multifunctionality that needs to be solved, because the concentrate obtained represents a by-product of the system.

5. Functional unit normalised on the input

   This option means taking as functional unit the amount of metal in the concentrate divided by the amount of metal in the ore entering the system, i.e. the recovery efficiency. This option stems from the consideration that ore grade is a determining parameter to the impact of the production system (see Sect. 3.5). Assuming that the amount of metal in the concentrate is due to two different aspects (the ore grade and the efficiency of the beneficiation stage), normalising the output on the ore grade allows to remove the first variable from the analysis. Thus, it would be perfectly feasible to compare different beneficiation technologies in different areas (as long as the compared technologies can reach the same level of recovery efficiency) and assess the effectiveness of the technology regardless of the ore grade, or, more generally, of the grade of the source. Removing the ore grade variable can help highlight the effect of other characteristics of the ore in the consumption and emission of the beneficiation plant. However, the results obtained using this functional unit need to be used carefully: they are ideal to compare the effect of a technology, but they risk hiding the relevant issue that lower grade implies higher impacts. This functional unit "hides" the impacts on the abiotic depletion of the recovered metal because the recovery efficiency is fixed. In summary, this functional unit might not be the most appropriate if the increase of the raw material recovery is one of the key messages of the project under evaluation. It would be more adequate if the focus is the optimisation of the process, i.e. reducing energy and material consumption to obtain the same output.

4.4 Multi-functionality

Co-products are a common aspect in metal processing. Ores often contain more than one valuable mineral or metal; thus, the joint production of metal concentrates or refined metals is often unavoidable. Nuss and Eckelman (2014) highlighted the interconnectedness of metals and mineral production: 42 out of the 63 investigated metals are obtained as co-products in multioutput processes. Co-products originate in different stages: at the concentration plant, at the refining plants, etc.

However, in the reviewed papers, only 11 studies mention co-products and three explicitly specify that their system is a single-output production. Amongst these studies, only Song et al. (2017) provide sufficient details about the quality of the co-products to properly discuss and evaluate the allocation.

The site-specific dependency of each product and the impossibility to find single-metal production route makes the use of the system expansion nonapplicable to solve system functionality in metal processing. For this reason, only economic and physical allocations have been found in the literature to solve multi-functionalities.

The reason why other studies do not mention multifunctionalities might be twofold.

On one side, it might be assumed that these studies implicitly adopted the surplus method to solve multi-functionality, allocating all the impacts to the main product, leaving the co-product burden free, due to small quantities or little revenue generated by this stream, as Memary et al. (2012) did.

On the other side, the predominance of concentrate as functional unit for beneficiation plants might explain for this absence. When the functional unit is the production of a certain amount of concentrate, the presence of other metals in the concentrate does not represent a co-production; it is rather a characteristic defining the product. Applying this method means moving the multi-functionality outside the system boundary.

Even though this procedure is not necessarily incorrect, since there is only one output, when looking at the complete production chain those impacts need to be allocated. In order to let the result of the study be useful for other practitioners, either the impacts have to be allocated or the co-product has to be described in all its relevant characteristics (and co-production routes) to allow for an allocation a posteriori.

4.5 Impact assessment

As discussed in Sect. 3.5, it was not possible to identify an average contribution of the flotation unit to the different impact categories. This aspect is common to the metal processing sector. Various studies normalising the results obtain different Areas of Protection (AoP) priorities. This is due to a very site-specific reality of mining activities (Song et al. 2017).

However, some impact categories have been found to be particularly relevant for mineral processing, and so hereafter, we will discuss which role can the flotation process have on them. These impact categories are water scarcity, resource use, land use, toxicity, cumulative energy demand and climate change.

Water scarcity has been highlighted as an issue of concern for the mineral processing sector. The role of flotation is not always explicitly mentioned as the source of this impact, but this might be due to the lack of detail in the system boundary and in the data available. When enough data are present to perform a process contribution at the level of the subprocess, the role of flotation as the largest contributor to this impact category is made evident (e.g. Canino et al. 2005). Water consumption in Chilean copper flotation plants, for example is estimated to be over 70% of that used for the entire mining operation (Donoso et al. 2013). For a detailed description of typical major water use in a plant, the reader is referred to Gunson et al. (2012), whereas the importance of closing the water loop has also been recently highlighted by Kinnunen et al. (2021).

Even though it is the whole process that determines the recovery efficiency, when it comes to beneficiation, flotation appears to be the key to resource use, since it is the process that more than others determines how much of the valuable metal reports to the concentrate stream and how much is discarded into tailings.

Land use is pointed out as a relevant impact category in many studies (Awuah-Offei and Adekpedjou 2011; Broadhust et al. 2015; Hong et al. 2018) mainly because of the long-time use of large areas. This aspect is mainly due to tailings, because of the large extension of tailing ponds. Flotation directly affects the characteristics of tailings, and the amount of recovery, but its recovery efficiency has a limited reflection on the amount of tailings. An increased recovery efficiency does not significantly decrease land occupation, because of the low concentration of metals in the tailings (Broadhurst et al. 2015). Its efficiency plays instead a role in determining impacts if the reference flow is the unit of valuable metals in the concentrate. In this case it changes the impact increasing the amount of reference flow, on which impacts are allocated.

In the studies analysed, most of the toxicity originates from tailings. To this extent, flotation plays a role in influencing the physicochemical properties of tailings, which in turn directly influence the emissions and thus toxicity impacts associated to tailings. Other direct environmental impacts can be related to the toxicity of flotation reagents; xanthates, for example, are common flotation collectors with a propensity to generate toxic compounds such as carbon disulphide (Shen et al. 2019). The development of evaluation tools to assess the environmental impacts of flotation reagents is an area that must be further developed (Shen et al. 2016), and one that is a prerequisite for more comprehensive life cycle studies.

Cumulative energy demand and climate change have been found to be intertwined and mostly correlated to electricity consumption (Hong et al. 2018). The contribution of flotation is linked to the energy intensity of the process. The few studies mentioning the energy demand from flotation reached different results (Canino et al. 2005; Pell et al. 2019). Far from being a contradiction, this confirms that energy consumption in flotation is connected to site-specific parameters (ore mineralogy in particular), but also interconnected to the operation of other processes in the supply chain. Finer grinding requires more energy but positively affects the efficiency of the downstream processes, flotation included. It is worth nothing, thus, that the reduction of particle size (including through well-established but also novel comminution technologies) should be the focus of further analysis in LCA studies, given the important implications of energy consumption on the overall environmental impact of mineral processing operations.

To conclude, flotation affects impacts mainly because it influences the quantity of recovered metal. Its effects are therefore particularly evident when the functional unit is the production of a certain amount of metal, whereas they are expected to be less noticeable when the production of a certain amount of concentrate is chosen as functional unit.

4.6 Key parameters

As reported in Sect. 3.6, five key parameters have been identified (ore grade, energy mix, ore mineralogy, production scale and allocation method) by the authors of the reviewed studies for what concerns impacts of the beneficiation stage. Here we discuss if these parameters have effects also on the flotation process considering it as a stand-alone unit.

Ore grade is a parameter acknowledged as an affecting factor of water consumption (Northey et al. 2014) and energy demand (Calvo et al. 2016; Memary et al. 2012), since a larger amount of ore needs to be processed for a given amount of metal in the final product. As water consumption and energy consumption are recognised as two main contributors to flotation impacts (Canino et al. 2005), it follows that ore grade will affect the impact results not only of the whole beneficiation stage but also specifically of the flotation process.

The same consideration is valid for the energy mix. In fact, in flotation operations, energy consumption is often described as the primary contributor to the impacts (Canino et al. 2005). The change of the energy mix (e.g. moving from a large fossil fuel share to a large renewable fuel share) can affect the results for most of the impact categories, as has been shown to be the case for small-scale mining operations (Beylot et al. 2021).

About ore mineralogy, Sect. 3.6 already underlined that its variance largely influences the concentrate grade (and extractable metal) and determines the quantity of reagents required. This means that it has a direct effect on the impacts of flotation as well as on tailing composition, and therefore on toxicity-related impacts.

The production scale has been demonstrated to affect the water consumption rate (Northey et al. 2013). As during the flotation process there is a high consumption of water, it follows that the production scale will influence the impacts of the flotation process. Considering this, in an LCA study it will be important to collect primary data of water consumption associated to that specific production scale and in terms not only of the amount but also of the origin (e.g. river water, tap water). Moreover, usually, a larger production scale allows the implementation of complex equipment and sophisticated features not possible when the scale is smaller especially due to economic reasons. This may allow an increase in the efficiency of the process even if in the flotation case this should be carefully evaluated especially in regarding of fine particles.

About the last key parameter, i.e. the allocation method, we should keep in mind that it is the entire beneficiation stage that determines the outputs of the process and so the presence of co-products, and not the single flotation process. Consequently, the influence on the results of the allocation method can be evaluated for the whole stage including the flotation process.

5 Conclusions and recommendations

In this review we have selected and analysed 29 scientific papers to investigate the role of the beneficiation stage in the LCA of metals and minerals with a focus on the flotation process. The analysis has encompassed every stage of an LCA.

The analysis of the system boundary revealed that the flotation process has not been investigated as a stand-alone topic; it rather appears mentioned in LCAs of the entire production process of minerals and metals. As a result, no established knowledge on the flotation process itself is available from an LCA point of view. Even the beneficiation process as a whole is mostly overlooked: (i) the beneficiation stage is most of the time embedded in the mining stage and (ii) whenever it is described in the system boundary with a dedicated unit, it is not disaggregated into sub-processes (e.g. flotation), except for eight cases in the literature.

The state of the art in LCA of mineral processing shows the predominance of literature data and aggregated data. The level of aggregation of data influences the system boundary and the way the flow chart is structured. Aggregated data also affect the interpretation of the results, limiting the analysis of process contribution and hindering sensitivity analyses.

The lack of studies focusing on the beneficiation stage and including details of the flotation process might be due to the fact that the beneficiation is a very material and site-specific stage, which makes it difficult to draw parallelism amongst the same processes applied to different sites. Amongst the hurdles of an LCA focusing on this stage, there is also the definition of the functional unit of a system producing an intermediate product in the value chain of metals and minerals (the flotation concentrate). In this paper, we presented some options to select the functional unit and address these problems. A survey amongst concentrate producers allowed us to identify the most compelling properties a concentrate must fulfil (concentrate grade, granulometry, other valuable metals or penalty elements contained in it and many other characteristics depending on the ore mineralogy). On the basis of these characteristics and on the goal of the LCA, we presented five possible alternatives for the selection of the functional unit.

Drawing conclusions on the LCA from scientific publications concerning the impacts of beneficiation remains a challenge. Studies addressing primarily this stage are scarce, and their results are often conflicting, or with scattered information. As shown in Sects. 3.1 and 3.2, there are also methodological aspects which make it difficult to draw comparisons amongst studies, such as different system boundaries and functional units. However, some impact categories have been found to be particularly relevant for the beneficiation stage. These impact categories are water scarcity, resource use, land use, toxicity, cumulative energy demand and climate change. In particular, the role that the flotation process can have on these impact categories is discussed.

Amongst the variables affecting the results, five key parameters have been identified: ore grade, energy mix, ore mineralogy, production scale and allocation method.

The beneficiation stage undoubtedly plays a relevant role in the LCA of metals and minerals, and its importance is expected to increase as exploitation moves towards lower-grade deposits. Its relevance is acknowledged and supported by some studies, even if the degree of its contribution in the mineral and metal value chains presents some conflicting results in the literature. We can draw some relevant recommendations to address some of the limitations found in the literature. First, we argue that greater efforts should be allocated to considering the various distinct operations within the beneficiation stage, particularly flotation, being the largest tonnage operation and due to its importance as a concentration process and its complexity. Second, the LCA community needs more primary data, less aggregated and presented in a more transparent way, not only for what concerns inventory of energy and materials, but also data characterising products and co-products. Similarly, data regarding key parameters should be provided. Sensitivity analyses to investigate how those key parameters can influence the results are also recommended. Third, some hotspots specific to flotation have been identified and should be used to orient data gathering when focusing on this process as part of detailed environmental assessments of the beneficiation stage. These hotspots are electricity consumption, fuel consumption and reagent use. Finally, in the authors' opinion, all the impact categories should be investigated, even at the preliminary level if data availability does not allow for a deeper investigation. In the impact assessment it should be kept in mind that the site specificity reflects also in the relative importance of different impact categories.

Appendix

List of the papers reviewed:

1. Althaus and Classen (2005)
2. Awuah-Offei and Adekpedjou (2011)
3. Broadhust et al. (2015)
4. Canino et al. (2005)
5. Durucan et al. (2006)
6. Farjana (2019a)
7. Farjana (2019b)
8. Farjana (2019c)
9. Grzesik et al. (2019)
10. Grbeš (2016)
11. Hong et al. (2018)
12. Li et al. (2008)
13. Li et al. (2017)
14. Mabiza et al. (2014)
15. Memary et al. (2012)
16. Nuss and Eckelman (2014)
17. Norgate and Haque (2012)
18. Norgate and Rankin (2000)
19. Northey et al. (2013)
20. Northey et al. (2014)
21. Pell et al. (2019)
22. Santero and Hendry (2016)
23. Sikora et al. (2018)
24. Song et al. (2014)
25. Song et al. (2017)
26. Tao et al. (2019)
27. Van Genderen et al. (2016)
28. Wang et al. (2015)
29. Westfall et al. (2016)

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Declarations

Conflict of interest The authors declare no competing interests.

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