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Environmental evaluation of metals and minerals production based on a life cycle assessment approach: A systematic review

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ABSTRACT

Many metals and minerals are the backbone of the clean energy transition. However, its extraction and production are known to be a source of various environmental impacts. The use of a multicriteria assessment tools such as life cycle assessment (LCA) to evaluate the environmental impacts of the production of these elements is still poorly developed. Therefore, science-based decisions to achieve carbon neutrality are limited as the whole life cycle is generally not considered. This systematic review was conducted to analyse three main aspects: (i) the context of LCA application in the mining industry, (ii) the methodology followed by LCA practitioners in literature, and (iii) the environmental impacts of different metals and minerals in multiple contexts. Seventy-eight (78) papers studying the life cycle of different metals and minerals were analyzed. The results of the methodology adopted in literature show some tendencies in terms of functional unit, system boundary, data source and software used. Among the studied elements, gold showed the highest impact in the global warming potential (GWP), terrestrial acidification (TP), water depletion (WD) and land use (LU). In the other hand, the comparison of those elements' global carbon footprint in 2021 showed that coal has scored the highest impact at $1.49\text{x}10^9$ t CO_2 eq. This study highlights also the need to conduct more LCA studies on strategic metals (Li, Co, Mn, REE) for the clean energy transition to reach the net zero carbon target. Moreover, a comparative analysis between the reported data in the Ecoinvent database and the average values extracted from literature showed aligned results for GWP while it reveals a gap for the other indicators.

1. Introduction

Mining minerals and metals have received a considerable attention in recent times and occupies the top agenda of most countries due to increased global market prices and demand of these products (minerals and metals) for the green technological industrialization. Furthermore, the recent health pandemic (COVID-19) enhanced resource nationalism and other geopolitical uncertainties (Mitchell, 2022). The International Energy Agency (IEA) defines the energy transition as shift to a more mineral-intensive energy system (IEA, 2022). For example, new electric cars use six (6) times more mineral inputs than the conventional cars, a phenomenon that exacerbates the intensive extraction of mineral and metal resources.

Hence, while the world is looking to a "green" energy transition, the resulting demand on metals and minerals will generate an impact on biodiversity that surpasses those avoided by climate change mitigation (Sonter et al., 2020). This soaring tendency for resources exploitation has inevitable impacts on the different spheres of the environment. Besides the big issue of finite resources depletion, mining activities impact water, soil, and air. Water is impacted due to the immense use of this resource (particularly in the arid regions) and its contamination by the leaching of heavy metals and metalloids from waste rock and tailings (Raghavendra and Deka, 2015). Impacting soil due to the billion tons of generated waste rock and tailings occupy millions of hectares. The emissions into the air are also a main alerting parameter, as the greenhouse gas emissions generated during this activity have reached approximately 8 % of the global carbon footprint (Cox et al., 2022).

Consequently, a worldwide scientific community has been called

Abbreviations: **CRIRSCO**, Committee for Mineral Reserves International Reporting Standards; **EU**, European union; **GWP**, Global warming potential; **IEA**, International Energy Agency; **ILCD**, International Life Cycle Data system; **IPCC**, Intergovernmental panel on climate change; **LCA**, Life cycle assessment; **LCI**, Life cycle inventory; **LCIA**, Life cycle impact category; **LU**, Land use; **SDG**, Sustainable development goals; **SJR**, Scimago journal and country rank; **TP**, Terrestrial Acidification; **UN**, United nations; **USA**, United state of America; **VOCs**, Volatile organic compounds; **WD**, Water depletion.

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upon to adopt sustainability metrics and life cycle thinking to provide support for the sustainable mining of these mineral resources. More strenuous efforts were spurred from the different stakeholders, especially with the global engagement either to lower the carbon emissions (i.e., Paris agreement), help implement the sustainable development goals set for 2030 or achieve the sustainable status as planned by the World Economic Forum by 2050 (Farjana et al., 2019). Recently the Columbian center on sustainable investment and the responsible mining foundation worked on a report that studied the status of sustainable development goals (SDGs) implementation in the mining industry (Kennedy et al., 2020). One of their key recommendations was publicly revealing the data concerning the impacts generated and their mitigation measures. This highlights the necessity of measuring the progress made to achieve sustainability and assessing its efficiency throughout the life cycle. To meet this aim, performing a complete and comprehensive assessment that avoids the burden shifting from one stage to another becomes a necessity. Thus, mining industries are starting to adopt the life cycle assessment method. According to ISO 14040/ 14044, this standardized tool enables the evaluation of the whole process's environmental impacts from "cradle to grave". It guides science-based decisions to define the hotspots and critical points where corrective actions should take place to lessen environmental impact. It is called holistic for covering the entire life cycle and providing a detailed assessment of the different potential impacts and their origins.

The trend of LCA application in the mining industry previously focused on the life cycle of the mine. Recently, the shift is towards life cycle of final product, which has become essential with a more integrated perspective of mined resources (Gorman and Dzombak, 2018). Paramount questions have emerged about resource extraction and resources recovery duration to alleviate its dissipation and losses (Gorman and Dzombak, 2018). It was remarked that the great attention of LCA practitioners had been geared towards the assessment of metals (Gold, copper, etc.) and energy fuel minerals (i.e., especially coal) (Segura-Salazar et al., 2019). Yet, the literature has agreed that LCA still needs some methodological improvements (Segura-Salazar et al., 2019), especially with the abiotic depletion indicator. This indicator is meant to assess the wasted resources that eventuate throughout the life cycle (Hauschild et al., 2017). Nonetheless, this cardinal indicator in the assessment of mining activities has been reported as one of the shortcomings of applying LCA in this field due to some facts detailed in Section 3 of this review paper (Segura-Salazar et al., 2019).

Several reviews have been published in the literature about the application of LCA in the mining industry. (Segura-Salazar et al., 2019), for example, have provided a statistical review of the literature, coupled with state-of-the-art concerning the integration of LCA with process simulation. In comparison, a recent review suggested integrating the geometallurgy into the previous approaches to upgrade the resolution of results obtained to achieve sustainability (Pell et al., 2021). Other reviews discussed the characterization results, detailing the environmental impacts per commodity (Farjana et al., 2019) or highlighting the differences between impacts per mass units and those related to annual production (Nuss and Eckelman, 2014).

This paper aims to provide a comprehensive review of all existing literature tackling the application of life cycle assessment in the mining industry. In this study, data from various literature sources were gathered, categorized, and analyzed. In addition, an analysis of tendencies and geographic distribution of LCA in this field has been performed. To the best of authors knowledge, this is the first study that discusses and compares the results of four crucial indicators (Global warming potential;(GWP), Terrestrial acidification;(TA), Water depletion;(WD) and land use;(LU)) of the different resources studied in literature in reference to Ecoinvent database. Also, the annual carbon footprint of different studied resources in literature is provided based on the data collected. Considering that this review is limited to the processing level, other phases including exploration and design of tailings management were incorporated into this study. Furthermore, limitations of this current study and future perspectives are detailed in order to provide a state-of-the-art reference material for any future LCA studies.

2. Methods

To carry out this study, a systematic and comprehensive review of 78 papers was conducted. These papers were gathered mainly from two (2) search engines; Scopus and Google scholar using appropriate key words as shown in Fig. 1. This search allowed us to gather all the papers published in this field since 1998 until the time of this study. More than 1200 published papers were found but only 78 papers were selected. The criteria used for the selection of the 78 published papers were: (i) respect for standards of conducting a Life cycle assessment (e.g., including/ mentioning the functional unit, clear system boundary, etc.), (ii) papers that deal with the application of LCA in the mining and processing operations, not resource recovery/recycling. (iii) papers written in English and indexed in Scopus. (iv) papers assessing different tailings management technologies were excluded. (v) papers tackling the social/economic aspect were excluded as the focus was given to the environmental perspective unless the environmental aspect was included. (vi) the last update of our selected papers database occurred on 30 May 2022. Detailed information of all the selected papers used for this study is provided in the appendix as Table A1.

The methodology used to conduct the four steps of LCA was also detailed and analyzed in the following sections. Different choices in literature, data quality, and other parameters have been discussed to show the tendency in literature and report the pros and cons of different methodological preferences. Classifying the primary or secondary data was according to the definition of European Commission (Fazio et al., 2013). However, the classification of system boundaries was reported the same as the authors declared. Details regarding the exact boundaries have been provided in subsection 3.2.1.

For the comparison of impact indicators (i.e., Global Warming Potential (GWP), Water Use (WU), Land Use (LU) and Terrestrial Acidification (TA)), only papers with the same system boundary (i.e., cradle to gate which refers to the end at the pre-manufacturing), functional unit (one mass units) and same unit for impact indicators (i.e., Kg CO_2 eq/t for global warming, m^3/t for water use and m2a for land use) were analyzed. Unfortunately, there are still no conversion factors from one LCIA method to another adapted to the mining industry unlike the construction sector (Dong et al., 2021). Thus, out of a total of 78 papers, only 70 met the criteria and were eligible for comparison. The methodology for each subsection is provided in the following sections.

3. Results and discussion

3.1. Life cycle assessment application in the mining industry

This section consists of a performed analysis of geographical distribution and tendency of LCA papers applied to different commodities. Building knowledge about these elements enables a global view to situate the advancements of LCA application in the mining industry and its level of maturity.

- Geographical distribution of LCA in mining

China, Australia, Brazil, USA, Canada, and Poland are respectively the top countries where LCA is primarily applied to the mining industry. This is not strange as, except for Poland, those countries are among the top 10 miners worldwide (Reichl, 2022). This geographical distribution is based on the place where the mining process occurs and not the authors affiliations. Table 1 shows the geographical distribution of different publishing countries on the topic of LCA in mining while highlighting the specific commodity studied per each country.

- *Tendency of LCA application in mining*

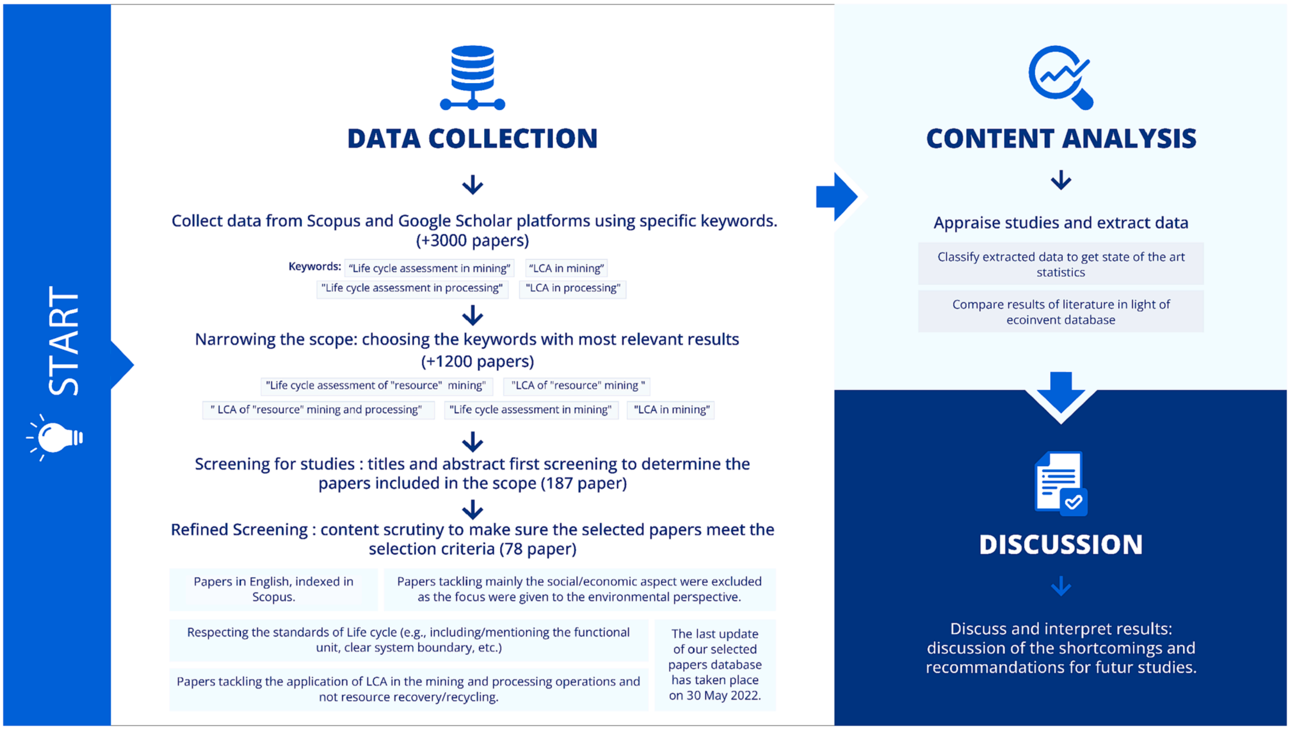

Fig. 1. Technical schema of this review's methodology.

A screening of Scopus-indexed papers assessing their impact was performed to analyze the trend in LCA papers studying different resources. To the best of authors knowledge, the earliest publication which studied the application of LCA in the mining industry was by Itsubo and Yamamoto which involved a life cycle assessment of non-ferrous manufacturing in 1999 (Yamamoto and a. R., , 1999). Subsequently other papers also assessed the environmental impacts of refined nickel in South Africa (Norgate and Rankin, 2002); and lead and zinc environmental impact, respectively, using LCA (Norgate and Rankin, 2002). Thus, the earliest application of LCA in the mining industry focused on metal industry. However, after collecting all the papers related to LCA in mining it became clearly evident that there has been a significant shift towards coal production since 1999. The enormous interest in quantifying coal impacts started with the paper that used life cycle assessment in mining planification (Mangena and Brent, 2006). As shown in Fig. 2, there was a keen interest in assessing coal mining, followed by copper and gold. Nickel, cobalt and aluminium are also emerging lately while the rare earth elements peaked in 2016/2017 in term of LCA publication numbers. However, there have been only a limited number of life cycle assessment (LCA) studies on lithium mining that have begun to emerge, with most of them appearing only since 2021.

3.2. Life cycle assessment stages analysis

3.2.1. Goal and scope definition

- *Functional unit*

The functional unit according to the ISO guidelines 14040/14044 implies detailing answers to the following questions: "What?", "How much?", "How well?", and "For how long?". Meanwhile, the preponderance of only the "what" and "how much?" answers in the literature is still more comprehensive than the other aspects. The existence of a framework dealing with such a specific field is still a missing puzzle that needs more efforts to be established (Bongono et al., 2020). To fill this gap, an urge to develop a framework adapted to the mining context is becoming paramount. Numerous authors have raised the issue of functional unit in the mining industry as a controversial topic that should be addressed (Segura-Salazar et al., 2019; Bongono et al., 2020).

Fig. 3, a shows an overview of functional unit distribution among the 78 published papers selected after performing a systematic review of literature. It could be observed that the use of 1 tonne of ore is dominating (47 %) in most of the literature for the different resources worldwide, followed by 1 kg of ore (25 %) especially for precious metals (gold and silver). The other forms of functional units used are split into quantification by energy, transport distance and volume. LCA practitioners in the coal mining industry consist of the majority using the quantity of energy (usually MJ) as a functional unit to relate the impacts to the amount of energy that could be produced from the mined coal (function). Furthermore, the studies where the transport distance was picked as a functional unit are mainly papers that studied the impact of transport on the mining operation.

The reason behind choosing the tonnage or ore production/treatment quantity may lie in data obtained from mining companies, which is usually linked to the annual production. Thus, making it easy to calculate one mass units either 1 t, 1 kg, etc. A review has provided recommendations for functional unit of a mineral product, metallic ore and for producing aggregates (Segura-Salazar et al., 2019). For minerals, including the intended application, would be an excellent asset to enable LCA studies comparisons. However, using one mass units was considered convenient as a functional unit for the metallic ore. Concerning aggregates production, providing details about aspects (range size, impurities, etc.) of the deposit enables the acquirement of a clear vision of the product's quality. Besides this, it was noticed during the published papers collecting phase that, some papers did not define the functional unit and presented characterization results without referring them to a unit. Meanwhile, it is recommended to adopt the common language spoken by LCA practitioners around the globe.

- *System boundary*

One pillar of the scope definition is delimiting the system boundary. The accuracy of this aspect influences the precision of the following steps either regarding collecting or analyzing data. Because the topic

Table 1
Geographic distribution of LCA publishing countries in the *mining industry*.

Country	Number	Commodity	Reference
China	18	Aggregates	(Hossain et al., 2016)
		Nickel–copper–cobalt	(Zhang et al., 2021); (Deng and Gong, 2018); (Wang, N.D.); (Yang et al., 2022)
		Lead–zinc	(Tao et al., 2019)
		Coal-lignite	(Ghadimi et al., 2019); (Zhang et al., 2018); (Tao et al., 2022); (Wang et al., 2016); (Liu et al., 2015)
		Vanadium titano magnetite	(Chen et al., 2015)
		Magnesia	(Li et al., 2015)
		Gold	(Hong et al., 2018); (Chen et al., 2018)
		Zinc	(Qi et al., 2017)
		Ferronickel	(Ma et al., 2019)
		Silicon	(Heidari and Anctil, 2022)
Australia	11	Copper	(Memary et al., 2012); (Norgate and Haque, 2010); (Sikora, W, N.D.)
		Iron ore	(Liu et al., 2020)
		Coal	(Adiansyah et al., 2017); (Adiansyah, 2020)
		Rare earth oxides	(Koltun and Klymenko, 2020)
		Zircon sand	(Gediga et al., 2019)
		Aluminium, copper, gold, iron and steel, lead, nickel, lithium, and zinc	(Strezov et al., 2021); (Moreau et al., 2021); (Kelly et al., 2021)
		Uranium-gold-copper	(Haque and Norgate, 2014)
Brazil	6	Coal	(Restrepo et al., 2015); (Silva, N.D.)
		Aggregates	(Rossi and Sales, 2014)
		Iron ore	(Ferreira and Leite, 2015); (Liu et al., 2020)
		Gold	(Kahhat et al., 2019)
USA	5	Coal	(Ditsele and Awuah-Offei, 2012)
		Aluminium	(Farjana et al., 2019)
		Zircon sand	(Gediga et al., 2019)
		Silicon	(Heidari and Anctil, 2022)
		Copper	(Moreau et al., 2021)
Poland	4	Coal	(Burchart-Korol et al., 2016)
		Silicon sand	(Mitterpach et al., 2015)
		Lignite	(Lelek and Kulczycka, 2021)
		Copper	(Moreau et al., 2021)
Canada	4	Uranium	(Parker et al., 2016)
		Iron ore	(Liu et al., 2020)
		Copper-zinc	(Reid et al., 2009); (Moreau et al., 2021)
Chile	3	Copper	(Castro-Molinare et al., 2014); (Moreno-Leiva et al., 2017); (Peña and Huijbregts, 2014)
Turkey	3	Lignite	(Şengül et al., 2016); (Erkayaoğlu and Demirel, 2016)
		Boron	(Türkbay et al., 2022)
South Africa	3	Sandstone	(Agwa-Ejon and Pradhan, November 2017)
		Iron ore	(Liu et al., 2020)
		Zircon sand	(Gediga et al., 2019)
Italy	2	Aggregates	(Simion et al., 2013); (Faleschini et al., 2016)
Peru	2	Gold	(Valdivia and Ugaya, 2011); (González-Campo et al., 2020)
Indonesia	2	Coal	(Aguirre-Villegas and Benson, 2017); (Tampubolon et al., 2021)
Hong Kong	2	Aggregates	(Hossain et al., 2016); (Gan et al., 2016)
France	1	Aggregates	(Jullien et al., 2012)
Croatia	1	Silica sand	(Grbeš, 2016)
Thailand	1	Limestone	(Kittipongvises, 2017)
Ivory Coast	1	Gold	(Yao et al., 2021)
Laos	1	Copper-silver-gold	(Islam et al., August 2019)
Malawi	1	Rare earth elements	(Pell et al., 2019)
Colombia	1	Gold	(Cano Londoño et al., 2019)
Philippines	1	Gold	(Cenia et al., 2018)
Norway	1	Copper	(Song et al., 2017)
Greece	1	Ferronickel	(Bartzas and Komnitsas, 2015)
Tunisia	1	Phosphate	(Issaoui, N.D.)

argued is the application in the mining industry, the majority (79 %) limited their system boundaries to the “cradle-to-gate” which meant, in most cases, from the mining and extraction operations to the gate of manufacturing. This includes crushing, washing, and/or flotation for minerals and aggregates, and obtaining the concentrate/refined concerning metals as shown in Fig. 4. This choice was generally justified by the independence of the technology used to deliver the commodities than the remaining value chain (Stewart, M, N.D). There was a contrast in including the transport to the gate and, therefore, making it unfair to compare the results obtained by each paper as they often named it “cradle-to-transport”. Nevertheless, a sensitivity study showed that an increase or reduction of 20 % in transport distance doesn’t affect the total impact (Hossain et al., 2016). Meanwhile, it was found that transportation contributes to (80 %) of open-pit mining carbon emissions (Liu et al., 2015).

For this, delimiting the boundary of the study should be declared accurately to allocate the results to their specific processes. It was noticed that some studies excluded some stages from their system boundaries either due to lack of data, negligible impact or proved to be marginal (Song et al., 2017). The problem of transparency also persists in the mention of system boundaries and the terminology related to them. Including more criteria to make a fairer comparison was recommended: the intended application and the nature of the deposit (Segura-Salazar et al., 2019). Recently, the trend has been growing towards the shift from the life cycle of the mine to the life cycle of the material. This would help in highlighting recovery and reuse processes in order to

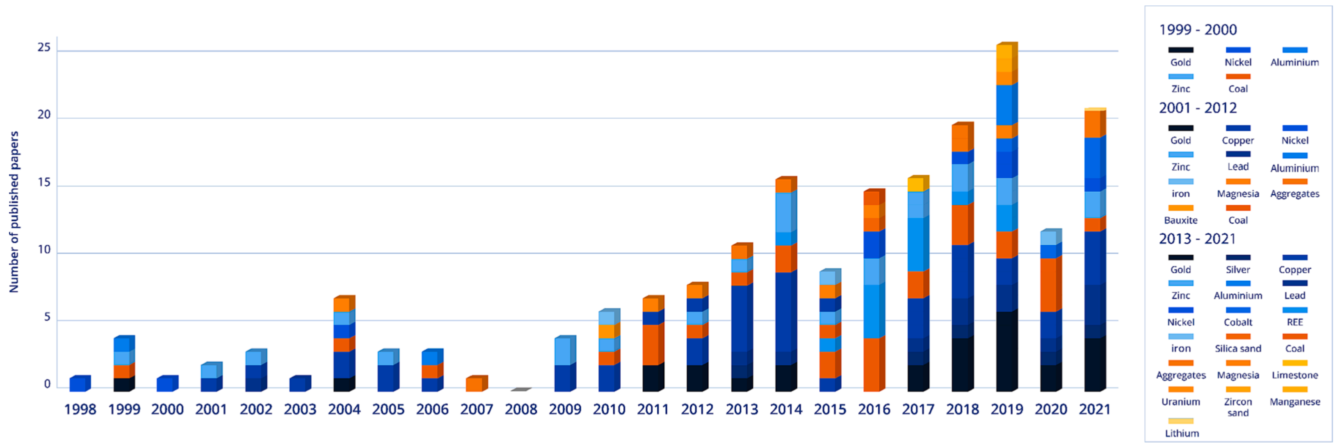

Fig. 2. Tendency of LCA applied in mining.

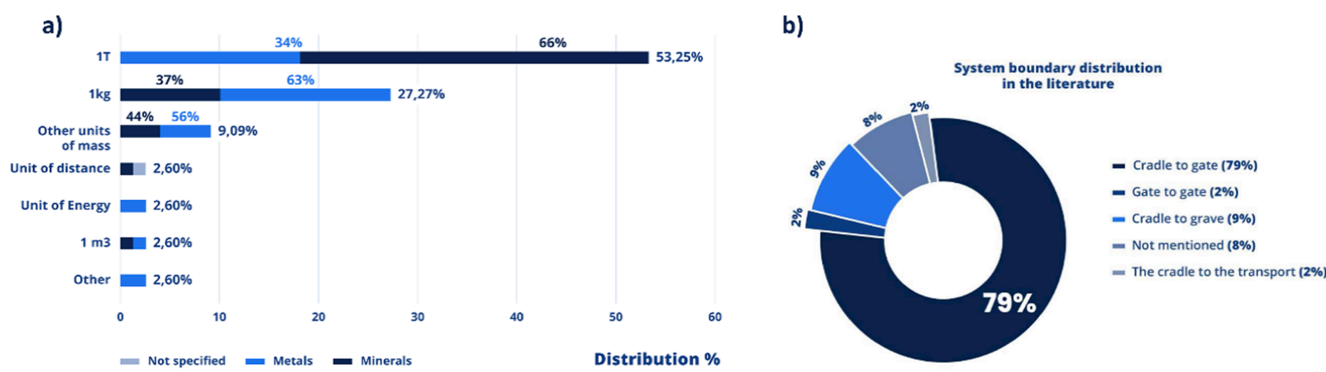

Fig. 3. The functional unit (a) and the system boundary (b) compilated from the literature.

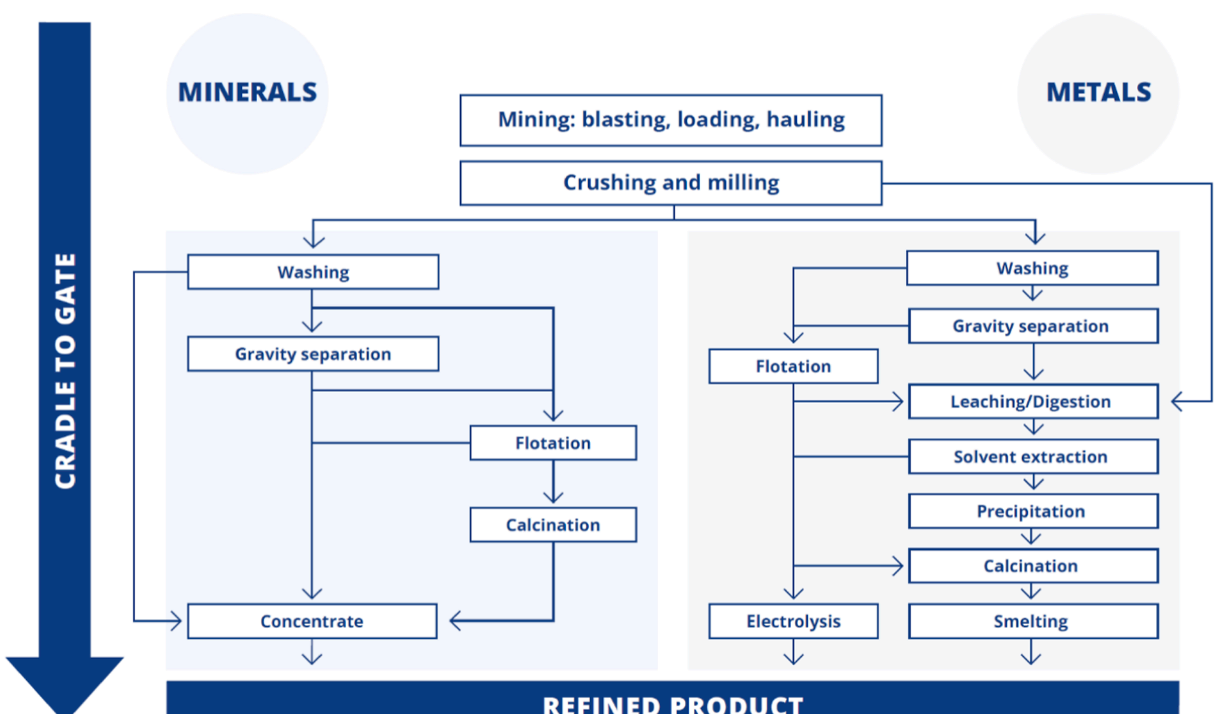

Fig. 4. System boundary of literature.

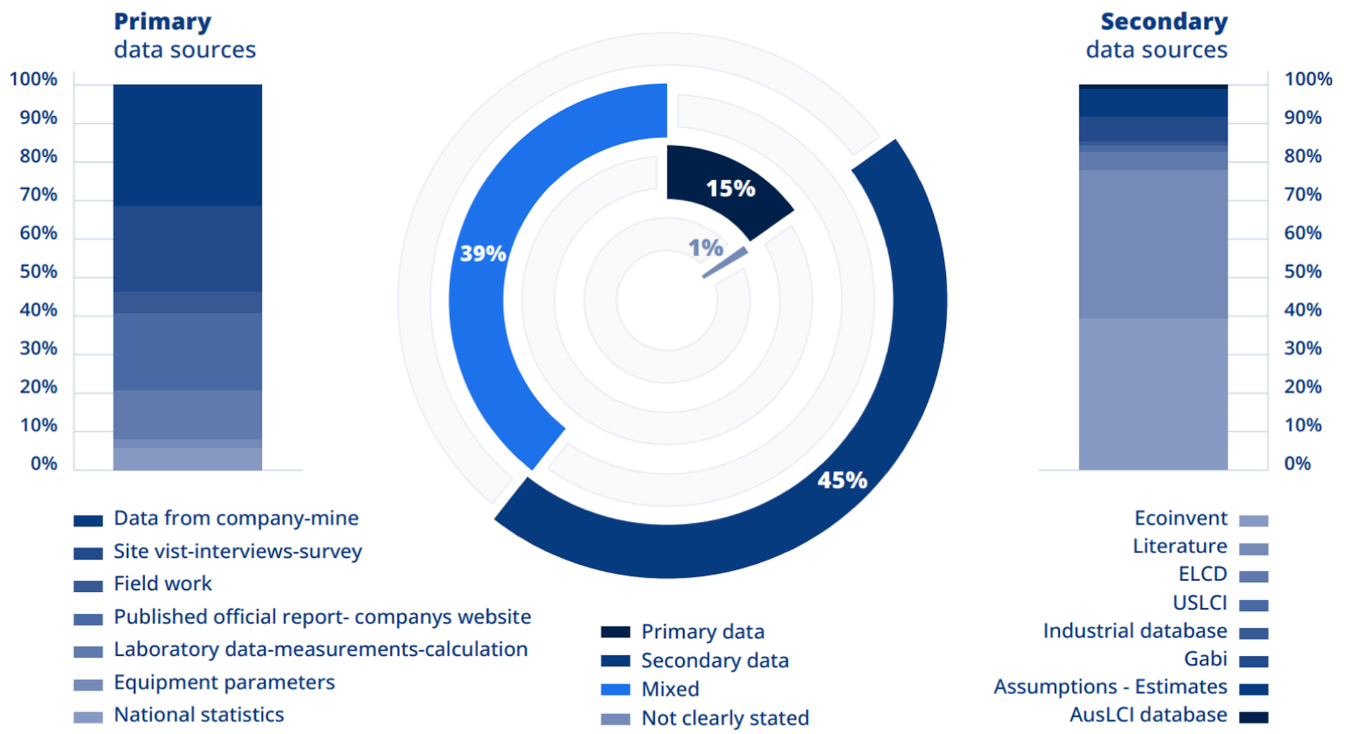

Fig. 5. Data quality and sources share in the literature.

reduce the losses and dissipation of large quantities of materials (Gorman and Dzombak, 2018). This framework would include all the metrics related to the whole life cycle of the mine, as well as the life cycle of the resulting product. This would shed light on the possibilities to design for recovery, the reclamation technologies and other more tangible solutions to achieve the sustainability (Reuter et al., 2013).

3.2.2. Life cycle inventory

Data quality is a crucial criterion that enhances or diminishes the quality of results and conclusions extrapolated in LCA. The practitioners of LCA around the globe face obstacles in gathering pertinent data for LCA format or for the local or regional use. (Restrepo et al., 2015). This can causes uncertainty in interpreting up to 70 % of the contribution to the impact because of lacking data, especially in regions where the LCA application is still growing (Restrepo et al., 2015). The Fig. 5 shows that secondary data is used by either adding it to complete the inventory or solely adopting it. The principal sources of secondary data are from literature, Ecoinvent database, etc. Primary data has been the main source in almost 54 % of papers selected for this analysis. It is primarily, data from the mining companies, interviews, surveys, visits to the mine, companies' websites, and officially published reports.

Nonetheless, some authors declared that the confidentiality of data in the industrial world is a solid obstacle to academia's evolution. This is the reason behind the limited information provided by the inventories in literature. Moreover, the aggregated data is still an issue that impedes the data reuse in other studies. In this concern, providing the details of each process will facilitate the continuity of database supply.

3.2.3. Life cycle impact assessment

- *Life cycle impact assessment methods*

The analysis of the Life Cycle Impact Assessment (LCIA) methods distribution in the selected papers shows that most authors have included the indicator conceived by the intergovernmental panel on climate change (IPCC). This indicator calculates the global warming potential. It is noteworthy that it is included in the other methods (ReCiPe, CML, etc.). Besides, it is the only indicator assessed in almost all the LCA papers considered for this analysis. ReCiPe and CML are primarily used in the mining realm representing 18 % and 17 % respectively. They were followed by Impact 2002+ (Jolliet et al., 2003) (12 %) and Eco-indicator (10 %) demonstrating the dominance of global methods compared to the regional ones.

In some cases, those global methods serve some regions better than those dedicated to them. This was the case for a study that used ReCiPe for the Australian context because the regional normalization and weighting factors were not operational with some impact categories like eutrophication and land use (Adiansyah et al., 2017). On the other side, an emerging global method such as Impact World + proved its reliability to the Brazilian context by reducing the uncertainty resulting from the lack of suitability to the context studied (Segura-Salazar and Tavares, 2021). In this study, the authors established a score in which they multiplied the categories assessed by the categories that showed a discrepancy lower than 50 % between the Ecoinvent processes and their baseline scenario. Based on this method, the Impact world + method was ranked first.

- *Software*

Around 50 % of the selected papers used Simapro software to run their calculations from which 42 % used Simapro version 8. This version was launched from 2013 to 2015 and is aligned with the period of those published papers. The Gabi and OpenLCA software have 14 % and 6 % shares. This illustrates a global tendency to use the Simapro software. While this is a tool for calculations and databases, it is still a source of uncertainty when comparing the different results obtained from different software. Results have shown that when using the same method (International Life Cycle Data system((ILCD) to run the same calculation with the same dataset via different software, Simapro has shown extra impacts of 22.7 % and 66.7 % for acidification and photochemical ozone formation respectively compared to other software (Silva, N.D.).

Minimum	Maximum	Literature Average	Ecoinvent value	
3.98×10^{6}	5.55×10^{7}	2.65×10^{7}	7.47×10^{7}	Gold
5.30×10^{2}	9.82×10^{4}	3.70×10^{4}	8.14×10^{4}	Uranium
1.70×10^{4}	8.70×10^{4}	3.14×10^{4}	2.23×10^{4}	REE
2.27×10^{4}	4.79×10^{4}	3.38×10^{4}	1.27×10^{4}	Silicon
1.17×10^{4}	3.56×10^{4}	2.37×10^{4}	3.95×10^{4}	Cobalt
2.69×10^{4}	2.69×10^{4}	2.69×10^{4}	1.40×10^{4}	Nickel
2.04×10^{4}	2.04×10^{4}	2.04×10^{4}	1.10×10^{4}	Lithium carbonate
9.27×10^{3}	1.18×10^{4}	1.01×10^{4}	8.01×10^{2}	Nickel ore
6.12×10^{3}	6.12×10^{3}	6.12×10^{3}	4.95×10^{3}	Zinc
1.80×10^{1}	5.85×10^{3}	1.17×10^{3}	1.22×10^{3}	Copper ore
2.25×10^{3}	5.00×10^{3}	4.05×10^{3}	1.10×10^{3}	Magnesia
1.91×10^{3}	4.78×10^{3}	3.50×10^{3}	5.84×10^{3}	Copper
1.70×10^{1}	4.52×10^{3}	3.02×10^{3}	4.72×10^{3}	Manganese
8.97×10^{2}	2.34×10^{3}	1.67×10^{3}	6.32×10^{2}	Lead ore
4.95×10^{2}	1.70×10^{3}	1.01×10^{3}	3.47×10^{3}	Boron
1.23×10^{3}	1.23×10^{3}	1.23×10^{3}	1.76×10^{3}	Alumina
7.33	8.95×10^{2}	1.94×10^{2}	6.18×10^{2}	Coal
3.75×10^{2}	3.75×10^{2}	3.75×10^{2}	8.20×10^{1}	Phosphate
3.20×10^{2}	3.20×10^{2}	3.20×10^{2}	—	Zircon sand
4.90	8.00×10^{1}	6.00×10^{1}	1.22×10^{1}	Bauxite
3.30×10^{1}	7.52×10^{1}	4.88×10^{1}	3.68×10^{1}	Silica sand
7.20	4.90×10^{1}	2.51×10^{1}	4.72×10^{1}	Iron ore
7.49×10^{-1}	3.20×10^{1}	1.12×10^{1}	—	Aggregates
2.76	2.76	2.76	2.96	Limestone

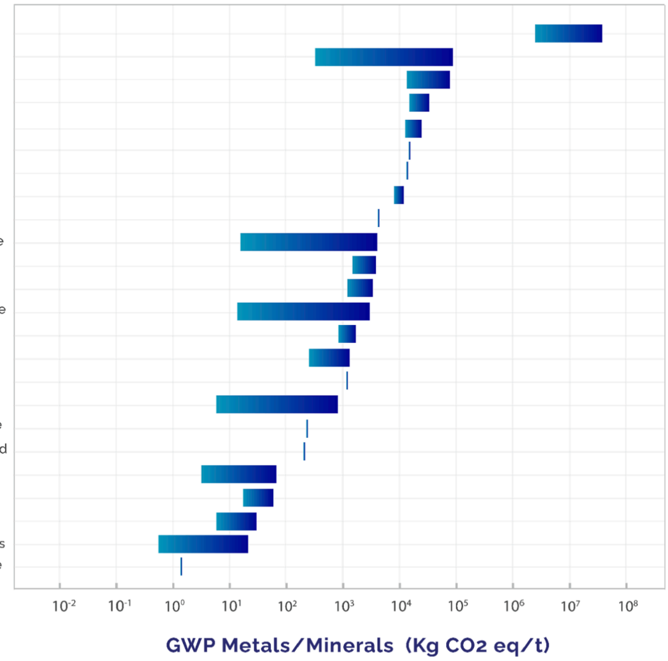

Fig. 6. The global warming potential (GWP) compilated from literature.

Minimum	Maximum	Average value	
5.61×10^{7}	6.85×10^{9}	1.49×10^{9}	Coal
1.93×10^{8}	4.07×10^{8}	2.87×10^{8}	Silicon
1.72×10^{8}	1.72×10^{8}	1.72×10^{8}	Alumina
1.19×10^{7}	1.67×10^{8}	7.95×10^{7}	Gold
6.75×10^{7}	1.50×10^{8}	1.22×10^{8}	Magnesia
4.97×10^{7}	1.24×10^{8}	9.10×10^{7}	Copper refined
3.40×10^{5}	9.04×10^{7}	6.04×10^{7}	Manganese
8.25×10^{7}	8.25×10^{7}	8.25×10^{7}	Phosphate
7.96×10^{7}	7.96×10^{7}	7.96×10^{7}	Zinc
1.15×10^{7}	7.84×10^{7}	4.02×10^{7}	Iron
7.26×10^{7}	7.26×10^{7}	7.26×10^{7}	Nickel refined
1.91×10^{6}	3.12×10^{7}	2.13×10^{7}	Bauxite
3.57×10^{6}	1.83×10^{7}	6.60×10^{6}	REE
7.76×10^{6}	1.77×10^{7}	1.15×10^{7}	Silica sand
3.86×10^{6}	1.77×10^{7}	7.20×10^{6}	Lead
1.83×10^{6}	6.30×10^{6}	3.74×10^{6}	Boron
1.99×10^{6}	6.05×10^{6}	4.03×10^{6}	Cobalt
2.89×10^{4}	5.35×10^{6}	2.02×10^{6}	Uranium

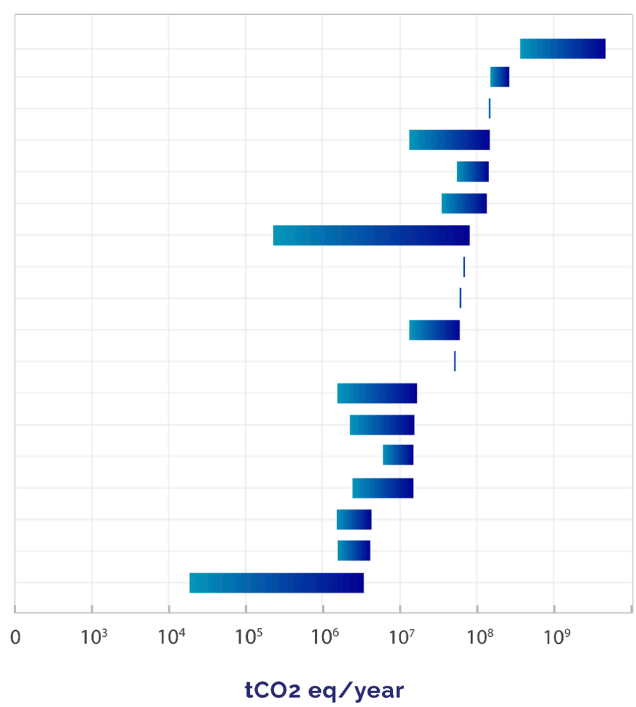

Fig. 7. Annual carbon footprint of different commodities production during 2021.

- *Comparison of characterization results from literature and Ecoinvent database*

This section illustrates the characterization results from the selected papers in Figs. 6, 7, 8, 9 and 10. Unified functional unit and unit of impact categories were the main criteria used to establish this database. For the functional unit chosen, one tonne of extracted ore for minerals and 1 tonne of refined metal for metals. The units designated for each category were the commonly applied ones. It should be emphasized that while ILCD reporting may advise caution in reporting certain indicators for metals due to their immaturity, our selection of these indicators was based on their extensive coverage in the literature. This ensured a representative comparison for most cases.

- *Global warming potential (GWP)*

The GWP indicator has the lion's share in most of the different applied methods (64 %) in the literature. This extensive use of this

	Minimum	Maximum	Literature Average	Ecoinvent value
Gold refined	2.07x10^{5}	2.50x10^{5}	2.29x10^{5}	3.30x10^{5}
Phosphate	1.37x10^{2}	1.37x10^{2}	1.37x10^{2}	4.14x10^{-1}
Cobalt refined	6.92x10^{1}	6.92x10^{1}	6.92x10^{1}	3.41x10^{2}
Zinc refined	1.83x10^{1}	1.83x10^{1}	1.83x10^{1}	4.02x10^{1}
Copper refined	6.56	6.56	6.56	5.16x10^{2}
Coal	3.77x10^{-1}	2.27	1.32	1.29
Aggregates	9.50x10^{-1}	1.27	1.11	—
Silica sand	2.21x10^{-1}	4.79x10^{-1}	3.17x10^{-1}	1.88x10^{-1}
Iron ore	5.60x10^{-2}	2.60x10^{-1}	1.63x10^{-1}	1.91x10^{-1}
Limestone	5.17x10^{-2}	5.17x10^{-2}	5.17x10^{-2}	3.40x10^{-2}

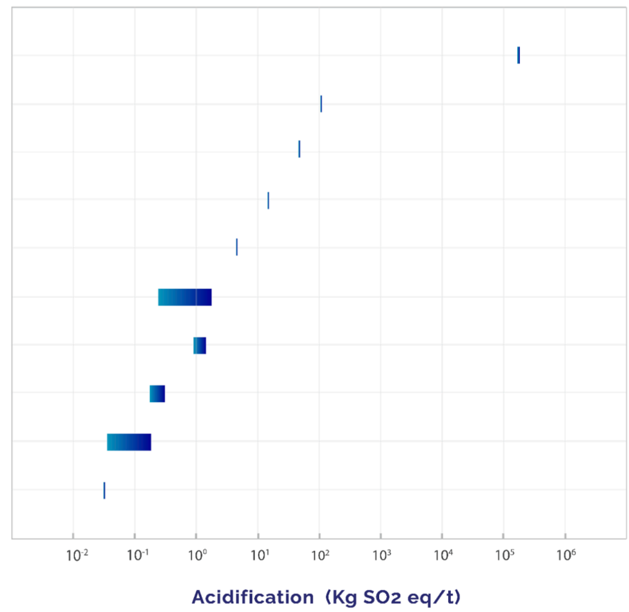

Fig. 8. Terrestrial acidification potential average in the literature compared to Ecoinvent processes.

	Minimum	Maximum	Literature Average	Ecoinvent value
Gold	2.59x10^{5}	4.61x10^{5}	3.30x10^{5}	7.55x10^{5}
Cobalt	5.90x10^{1}	4.54x10^{3}	2.30x10^{3}	4.82x10^{3}
Phosphate	9.63x10^{2}	9.63x10^{2}	9.63x10^{2}	6.53x10^{-1}
Lead ore	1.29x10^{2}	1.29x10^{2}	1.29x10^{2}	2.85x10^{1}
Iron ore	1.00x10^{1}	1.00x10^{2}	5.54x10^{1}	3.42x10^{-1}
Copper	3.49x10^{1}	9.60x10^{1}	5.70x10^{1}	1.87x10^{2}
Lithium carbonate	7.7x 10^{1}	7.7x 10^{1}	7.7x 10^{1}	1.3x10^{2}
Zinc	6.62x10^{1}	6.62x10^{1}	6.62x10^{1}	5.24x10^{1}
Boron	5.60	2.07x10^{1}	1.34x10^{1}	8.69x10^{1}
Silica sand	1.24	5.83	3.65	2.91x10^{-1}
Coal	1.78x10^{-1}	4.50x10^{-1}	3.14x10^{-1}	2.87

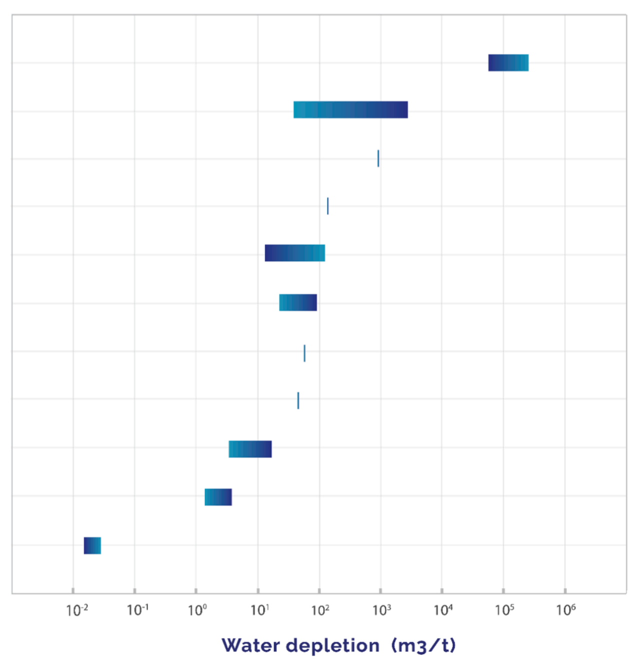

Fig. 9. Water depletion average in the literature compared to Ecoinvent processes.

indicator enabled a fair comparison between many different resources studied in the literature. Hence, a comparison of the average GWP value calculated from literature and Ecoinvent processes using the ReCiPe 2016 H midpoint (Huijbregts et al., 2017) was performed. The choice of Ecoinvent processes was considering the nearest scope of different commodities to this review's scope, while the choice of the ReCiPe method is justified by its common use in the mining industry.

It is important to know that minerals have a lower impact than metals (except copper and lead ore) based on one mass units. This is essentially due to smelting and refining which are intensive energy consuming processes necessary for metal refining. Refined gold has the highest impact on GWP with an average value of 2.65x10^{7} kg CO2 eq/t. However, a value of 1.17x10^{9} kg CO2 eq/t that is extracted from a study in the Ivory Coast was excluded from this comparison. The authors have justified this high value to be result of including the offsite emissions, which have not been considered in other gold mining studies (Yao et al., 2021). However, the values for this commodity in this impact category were concentrated in the range between 1.76x10^{7} and 5.55x10^{7} kg CO2 eq. Yet, the value included in Ecoinvent is in the same magnitude order as the literature average.

For most resources, the literature average and Ecoinvent values are aligned or in the same magnitude order. Yet, nickel ore showed lagged results even if the paper from which those values were extracted was based on Ecoinvent values. This might be due to the updates in nickel processes included in Ecoinvent 3.7 that followed the publication of the previous results (Farjana et al., 2019).

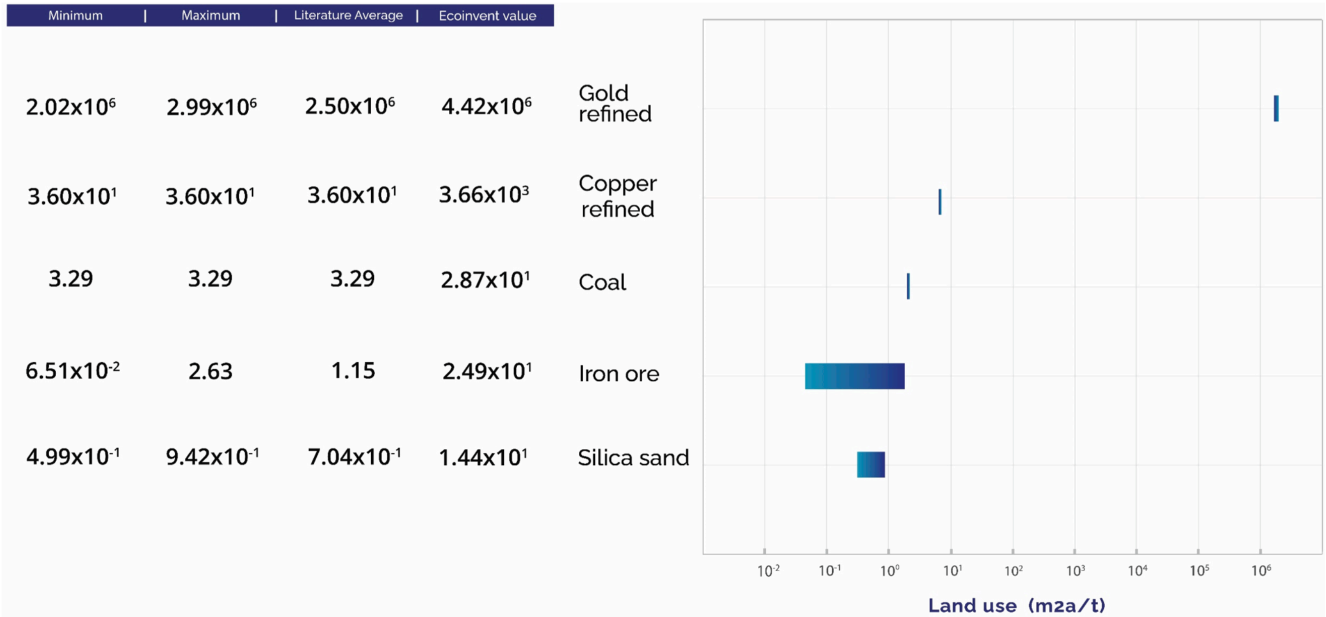

Fig. 10. Land use score average in the literature compared to Ecoinvent processes.

It can be concluded that mineral resources had the lowest mining impact except for magnesia, with an average of $4.05x10^3$ kg CO2 eq to produce/process 1 tonne of ore. In contrast, the maximum average value for metals is $2.65x10^7$ kg CO2 eq to produce/process 1 tonne of gold ore. This gap in carbon footprint between the metal and mineral industry is because metals are energy extensive, especially during processing and refining. However, it is worth mentioning that almost 84.2 % of global resources production are minerals, while the worldwide consumption of metals remains at 2.8 % (Franks, 2020). Consequently, this must be considered when deciding which resource category has a crucial impact on climate change from a more holistic perspective.

- *Annual Global Warming Potential (GWP) for different commodities*

Based on the data collected in the literature, the average GWP values for the different resource were multiplied by their annual production in 2021 (according to the USGS). The results reveal that coal has a higher impact with 1.49 Gt CO2 eq/year. This is not due only to the impact of its mining, but also to its massive production (7.66 billion tonnes annually). It is noteworthy to indicate that this calculation concerned just the primary resources and used the average GWP impact from literature with the system boundary indicated in section 4. Unlike the other resources, gold is mined in a limited quantity (3000 t) but its impact is considered very harmful. Even though it is extensively mined, iron ore still have a lower impact than most of the studied commodities, unlike steel production that have a much higher impact that almost reaches $3.33x10^{12}$ kg CO2 eq/year and that will put it on the top of this list of most polluters. This perfectly emphasizes the importance of the boundary adopted to decide on different materials sustainability and the reordering it may induce.

- *Global warming potential breakdown based on technologies adopted*

In line with the tendency of miners to adopt open pit mining as it generates higher net product value compared to the underground, the LCA papers published in this matter follows the same pattern (Ben-Awuah et al., 2016). Almost 50 % of the selected papers studied open pit mining scenarios, followed by 15 % studying underground cases, 15 % assessing both surface and underground and 1.25 % studied artisanal and alluvial mining.

The average value of GWP resulting from an open pit per one tonne of ore produced for metals is about $9.03x10^7$ kg CO_2 eq whereas the underground is $4.29x10^6$ kg CO_2 eq. For minerals the open pit method also had the highest value compared to underground with $1.17x10^4$ and $2.23x10^2$ kg CO_2 eq. However, this could be justified by the few papers studying the underground, which might not be representative for this extraction method.

- *Acidification*

In contrast to the focused attention on the GWP, terrestrial acidification was not exhaustively studied in the literature even with the potential of acid mine drainage in some case studies. However, since only the cradle to gate was considered, and only a few papers considered the waste treatment, this indicator wasn't appearing in most papers. Due to the extensive amount of acid solutions used during the cyanidation process, gold mining was found, based on our selected papers, to be the most contributor to terrestrial acidification with $2.29x10^5$ kg SO2 eq per tonne. To address this issue, several solutions were investigated, as for instance, the cupric chloride and thiosulphate that were found to be an efficient emerging alternative to cyanidation (Elomaa et al., 2020; Cairncross and Tadie, 2022).

Regarding phosphate extraction, a study by Issaoui et al (2022) in Tunisia reported an emission of around 135,418 metric tonnes of SO_2 eq per year in addition to the NOx emissions from nitrate explosives aggregated in the value of $1.37x10^2$ kg SO_2 eq per 1 t of phosphate (Issaoui, N.D.). However, there were no other values in the literature for the same boundary to enable a fair comparison. However, other minerals like coal (1.32 kg SO_2 eq), aggregates (1.11 kg SO_2 eq) and Silica sand ($3.17x10^{-1}$ kg SO_2 eq) were approximately in a consistent order of magnitude. For this reason, a calculation using Simapro software was performed with the same LCIA method for the two existing scenarios: Morocco and Florida (US). The values found were $4.14x10^{-1}$ and $2.01x10^{-1}$ kg SO_2 eq per 1 t of P_2O_5, approximately 300 and 600 folds, respectively.

- *Water depletion*

This indicator was understudied as only 16 % of the papers selected included it. The highest value of ($3.3x10^5$ m^3) is related to producing 1 t of refined gold. This exhaustive use of water is related principally to the nature of gold metallurgy. The refining process significantly contributed to this result as the consumed water during mining was 0.8 m^3 for 1 t of ore versus almost 260,000 m^3 for 1 t of refined metal (Norgate and Lovel, 2006). The cyanidation in the hydrometallurgy processing and conventional low grade of gold are the key parameters behind the colossal water consumption for this precious metal (Norgate and Jahanshahi, 2010).

In contrast, copper had the lowest values in this category, probably due to its relatively high grade compared to the precedent. For the case of minerals, the minimum value is attributed to the processing of 1 t of coal. The mining phase that consumes a huge percentage of water is flotation and/or washing. The comparison to the Ecoinvent database showed lagged results, especially phosphate and iron ore. For iron ore, the LCIA method was the same, and the water consumption in the papers ranged from 2.01×10^1 to 1.02 m^3/t, while it was almost in the same range (6.62×10^{-1} m^3/t) in Ecoinvent inventory.

- *Land use*

Despite the relevancy of this indicator to the mining industry's environmental assessment, it is still an under-assessed impact category. Only 15 % of the database included this impact category in their analysis. An aggregated indicator has been established by adding the values of agriculture and urban land use to generate a single score. The unit m2a/t was used in most selected papers and thus was applied. In line with the precedent indicators, also gold had an immense impact with 2.95×10^2 m2a/t, followed by copper (1.3 m2a/t) for metals. It was the only value obtained for metals from this analysis since much of the rest did not include this impact or used a different unit (i.e., m^2. year/ t, %, etc.). This impels an urge to calculate and conceive conversion factors for the mining industry in line with the concrete industry, that have recently known a matrix to convert the result of different indicators from different methods and made it possible to compare fairly.

The mineral resources had less value than metals, mainly due to the lower impact on land use generated by minerals since the overburden, in this case, is much lower than other metals, especially the precious ones. The gaps in the land use indicator between Ecoinvent, and literature values might be related to the significant updates in the ReCiPe method 2016 in the case of silica sand and copper which both used previous versions.

Including this indicator when assessing this sector's environmental burden is paramount to get an accurate interpretation of results. This would help not just provide a quantification of the impact but also cumulating some knowledge about the different impacts involved in the land transformation process. It will help develop more efficient land reclamation strategies since this indicator was relatively recently established in 2010 (Hauschild et al., 2017). Consequently, an exhaustive discussion of the results enables accumulating knowledge and performing well-oriented decisions on this matter.

As it could be observed, the GWP indicator had the narrowest gap between Ecoinvent and literature values as it is the most mature indicator in LCA, and the most unified impact pathway adopted in LCIA methods. Among the different commodities, copper was one of the most studied. However, several studies reported a gap in LCA performance for this commodity between hydrometallurgy and pyrometallurgy, which necessitate more efforts in both ways (Yang et al., 2022). Also, many updates have been included in Ecoinvent concerning metals and minerals extraction and processing which might result in significant gaps between different versions. However, some commodities such as phosphate hasn't been updated since 2007. Meanwhile, many updates have affected this industry since then and resulted in models that no longer reveal the actual process.

3.3. Limitations, recommendations, and future perspective

- *Limitations of LCA application in mining*

Through this analysis, the limitations declared by the authors of selected papers were collected and categorized according to the concerned step of LCA. Only few papers (13 %) dedicated a whole paragraph to this matter. However, almost half of the papers (54 %) didn't claim any limitations of their studies. This reveals the lack of transparency that humpers maintaining the coherence of cumulative scientific knowledge and further the advancements in related studies. The limitations related to LCA application in the mining industry were classified into 13 categories: data availability, data uncertainty, data allocation, data aggregation, impacts categories, LCIA methods, results comparison, LCA frameworks, exclusion criteria, boundary, LCI and software.

- Data availability: This concern is shared among all LCA practitioners in different domains and geographic regions. The authors claimed a lack of geographically-adapted, publicly available, and high-quality data. Furthermore, issues related to lack of data for emissions from the most used machines are still persisting (Mitterpach et al., 2015). Whiles, others reported the unavailability of fugitive atmospheric emissions (Kittipongvises, 2017). National data convenient for conducting an LCA is among the main concerns in several countries (Adiansyah et al., 2017). In addition, some essential data to estimate mining operations' environmental impact, such as water treatment and discharge, remains unavailable (Van Genderen et al., 2016). Consequently, promoting of publicly available datasets is becoming an argument to provide accessible data given the shortage of primary data.
- Data aggregation: Many papers have reported the difficulty of finding disaggregated data, which enables the recycling of data in other studies and avoids the replicated calculations of the different impacts (Memary et al., 2012; Erkayaoğlu and Demirel, 2016; Jullien et al., 2012; Pell et al., 2019). Giving the example of the aggregated impact of transport in different mining operations contributes to the issue mentioned before.
- LCIA methods: Remarkable deficiency in current LCIA methodologies was mentioned in terms of their capacity to analyze significant impacts from mining (e.g., salinization of water resources, aqueous acidification, and solid mineral waste) (Broadhurst et al., 2015). An inconsistency was declared regarding the Australian indicator of normalization and weighting with their regional context in south Australia and found ReCiPe more applicable instead (Adiansyah et al., 2017). For most countries, there is no available national LCIA method. While others claim the exclusion of land use potential for mining sites, so they replaced it with another method (Şengül et al., 2016). Accordingly, this approach was confirmed, and most of the available LCIA method is still inconsistent concerning this impact category (Faleschini et al., 2016).
- Data uncertainty: The quality of input to run a calculation in LCA is the leading indicator of the results reliability. The primary data is often missing so the authors mostly complete these gaps from Ecoinvent or literature, which generates an uncertainty associated with those generic datasets (Memary et al., 2012; Şengül et al., 2016; Kittipongvises, 2017; Broadhurst et al., 2015). Additionally, certain emissions arising from mining procedures are not adequately documented in existing literature, which impedes their verification in the context of other studies. (Jullien et al., 2012).
- Other: Data collection, especially for the exploration phase of mining, was reported to be challenging to complete the mining process's life cycle (Parker et al., 2016). The boundary has been

among the restrictions that don't include specifically the end of life (Ghadimi et al., 2019). Considering the precedent insights, comparing the results derived from this process is tricky due to the discrepancy in system boundaries applied, data quality, allocation procedure, databases, and life cycle impact assessment methods (Pell et al., 2019). The exclusion criteria in the literature also contribute to the uncertainty of some results. This distinction is further exemplified in studies claiming the exclusion of dust emissions from the mining site, others exclude the weighting and normalization and other authors didn't mention the quality of the mined ore during the operation period (Memary et al., 2012; Adiansyah et al., 2017; Jullien et al., 2012). It was also reported that most literature cut out the emissions from tailings (Beylot and Villeneuve, 2017).

- *Abiotic depletion indicator*

The abiotic depletion indicator is still a bottleneck in the process of LCA application in the mining industry. Even though several efforts have been made during the last 20 years to develop life cycle impact assessment methods, the assessment of mineral resources remains a not-assented method worldwide. One of the general issues reported in the literature is the dilemma of main concept definitions. The definitions given by the geologists, economist and LCA practitioners for the same concept (e.g., Mineral reserve, mineral resources) have been proven to be referring to different things. As the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) would name "mineral resource" to the concept that is referred to in LCA as "reserve base". Accordingly, the so called "mineral reserve" by CRIRSCO is the "economic reserve" in LCA terms. Hence, those different definitions confuse the concept of resource with reserves while the latter is a part of the preceding (Drielsma et al., 2015).

Moreover, the notion of depletion and availability itself has always been a source of debates that discussed two paradigms, as mentioned by John E.Tilton (Tilton, 2002), which can be categorized as optimistic and pessimistic future views. The first perceives resource depletion as an economic matter steered by market demand. The second on the other hand, is mainly based on the fixed stock paradigm that considers mineral resources as a finite quantity. The challenge here is that LCA practitioners are fluctuating between those paradigms, which is perplexing due to their contrasting difference in considering natural resources (Drielsma et al., 2015). Regardless, it is worth noting that a resource might have high resource depletion potential and be available economically and vice-versa. Consistently, the use of "dissipation" instead of "depletion" was suggested (Beylot et al., September 2020). Resource dissipation was defined as the non-accessible resources to future users which hampers its function due to economic and technological factors (Beylot et al., September 2020).

To resolve this, new efforts have been channeled into developing new indicators or updating the previously conceptualized indicators. A new indicator were developed for boron (Türkbay et al., 2022) and cesium (Vidal et al., 2020). In addition, a crustal scarcity indicator for long-term global essential resource evaluation in LCA was performed (Arvidsson et al., 2020). Recently, new work has been carried out where they developed midpoint and endpoint characterization factors considering dissipative resources. This study showed that having more impact on midpoint indicators is related to large resource flows, while the impact on the endpoint is relatively dependent on the resource market price (Charpentier Poncelet et al., 2022). Notwithstanding, many recommendations have taken place in this regard. On one hand, it was recommended to stand on one specific perspective when defining and calculating resource depletion. On the other hand, in-depth updates of the life cycle inventory were encouraged to update the existing datasets related to resource dissipation with more recent ones (Beylot et al., September 2020).

3.4. Sensitivity analysis

Only 31 % of our selected papers (21 paper) included a sensitivity analysis. These papers mainly focused on assessing the impact of electricity with different grid mixes (Ditsele and Awuah-Offei, 2012; Broadhurst et al., 2015; Farjana et al., 2019; Farjana et al., 2019). Hence, the contribution of the critical parameters was of great interest in multiple studies (Li et al., 2015; Gediga et al., 2019; Guimarães da Silva et al., 2018; Zhang et al., 2019).

- Electricity and energy consumption

The sensitivity analysis has addressed in some studies the consumption of electricity and its grid mix. When assessing its consumption during the desulfurization flotation process, the consumption of electricity decreased by 40 %, resulting in a 31 % and 26 % reduction in climate change and fossil fuel depletion (Broadhurst et al., 2015). In other studies, two different grid mixes were compared (i.e., from wind power and base case from hydropower) for the refining process, it was concluded that adopting energy from wind power would significantly reduce up to 58 % the impact on climate change (Farjana et al., 2019).

On the other hand, sensitivity analysis was performed by varying around ± 25 % of the selected parameters, and it was concluded that energy consumption was susceptible to ore grade and metal recovery. Another study conducted the sensitivity analysis by reducing and augmenting the emission factors by 10 % and 20 %, respectively, related to the top contributing factors to VOCs emissions. Hence, the emission factor related to electricity production from coal had the highest impact, whereas the change was not remarkable for the rest (Peng et al., October 2020).

- Transport mode and distance

It was found that even with the change of ± 20 % of transport distance, it didn't remarkably influence the final impact even though the fuel used was diesel (Hossain et al., 2016). Another aspect related to the transport parameter's sensitivity is the transportation mode. Taking an example of the Chinese context, it was found that the principal mode of transportation is railway, highway, and waterways, which contributed to 7.06 %, 10.3 %, and 19.1 % to volatile organic compounds (VOCs) emissions, respectively (Aguirre-Villegas and Benson, 2017).

- Key contributors

It was proved that even a reduction of 5 % in the main contributor to the impacts induces a significant decrease of this element in several categories (Zhang et al., 2021). Another studies evaluated key parameters' sensitivity to direct and indirect GHG emissions (Guimarães da Silva et al., 2018). These studies found that fugitive emission factors were responsible for direct coal emissions, which solicits a particular emphasis when building inventories. Meanwhile, for the indirect emissions, diesel oil production had the higher impact (Guimarães da Silva et al., 2018). Overall, the main contributor that has been assessed and had a significant impact was, in most cases, energy consumption.

- Other

Besides the critical parameter sensitivity that captivated the attention of LCA practitioners, ore grading was one of the studied parameters. It showed an influence of the electricity consumption inside the plant but didn't change much regarding local impacts resulting from diesel consumption as a fuel (Jullien et al., 2012). Another study assessed the allocation methods' sensitivity (i.e., mass and metals). However, it was demonstrated that the results don't change remarkably as the difference between the two methods varied just by 0 % and 2 % (Van Genderen et al., 2016). Another perspective to study the sensitivity of LCA application in the mining industry was to compare scenarios with sustainability indices related to emergy analysis. The results showed a significant mitigation associated with decreasing imported resources and water input in alluvial mining.

3.5. Recommendations and future perspectives

Only the extraction and processing of the mining activity have been at the center of LCA community interests. Waste management, exploration and design were excluded at most times. However, the major disasters caused by the mining activities resulted from the disposal techniques of tailings or the acid drainage and infiltration of toxins in the soil and ground water. Also, the phase of planification and exploration for extraction has been neglected from this perspective. Meanwhile, integration of those two phases in the life cycle analysis of the mining industry might increase the accuracy and certainty of the impacts communicated for each mining scenario. The comparison of different scenarios of tailings management and exploration techniques will surely enable decision-makers around the globe to take the more sustainable path to approach both stages.

- LCA of exploration strategies and design

Planning for a new mining operation is the crucial step that defines the consequences of this activity. It is the step where the economic, environmental, and even social impacts can be estimated. However, until recently, only the technical and economic aspect have been gaining the major focus that influenced the scheduled steps. Integrating the LCA method in the exploration phase has been proven to be a robust tool that assists in achieving responsible mining (Wall and Pell, 2020). They demonstrated that applying this method helps anticipate the impacts and thus schedule prevention strategies to hamper its occurrence. Another study by the EU stressed the significance of optimizing the first two stages of mining activities (i.e., design, and exploration). It was considered an efficient sustainable management technic to diminish the waste generated by this industry rather than focusing on the conception of methods to reduce it after its generation (Community, 2019). A full review has been done to introduce a revolutionary environmental design to demonstrate the foremost role of sustainable assessment tools in this process (Stewart et al., 2003). Despite the paramount role of applying LCA method in this early stage to enhance the following phases, few LCA papers have tackled this aspect (Pell et al., 2019). Hence, more efforts and papers that test different scenarios should be performed to demonstrate its utility for all stakeholders involved.

- LCA of Tailings storage and management

Most studies tackling LCA in the mining industry were limited to ore extraction and processing and neglected waste management, which is a crucial stage of this activity when considering its environmental assessment. Hence, this leads to a simplistic interpretation of the real impact. A recent review (Beylot et al., 2021) that studied LCA papers assessing tailings management has emphasized that the literature has known an initiation of tailings disposal's LCA modeling since 2008 with (Doka, 2008) (Doka, 2008), and has gained increasing interest from 2014. The majority (46 %) of generated tailings are from the copper mining industry, followed by gold 21 %, iron 9 % and coal 8 % (Oberle et al., 2020). The literature showed that LCA practitioners had almost the focus aligned with these results, as the most studied tailings using LCA were copper ore tailings (e.g., (Beylot and Villeneuve, 2017). Several techniques have been emerging lately to optimize either the generation, storage, or valorization of those tailings to mitigate their environmental impacts. It has been proven that desulfurization flotation before dewatering and disposal reduces human toxicity, and ecotoxicity by removing sulfur and lowering zinc mobility (Broadhurst et al., 2015). Moreover, coupling the mining and cement industry is among the circular resolutions for tailings valorization. The use of treated tailings as supplementary cementitious materials has been studied in several papers (Vargas et al., 2020; Syed Hasan et al., 2021). The storage of tailings was assessed considering the short and long-leaching and emissions accounting (Beylot and Villeneuve, 2017; Muller et al., 2022). In addition, storage technics were also a subject of assessment (e.g., submerging the tailings to shorten the surface vulnerable to oxidation, densification or optimization of geographical stabilization) (Reid et al., 2009). The efforts to achieve zero-waste mining have increased since the SDGs' implementation. Consistently, the application of an integrated assessment of multiple scenarios related to tailings management is turning to earn more interest not only to define the hotspots but also to verify the possibility of burden shifting.

- Future perspectives

In line with the limitation section, only 13 selected papers have made recommendations in response to the limitations and problems declared or suggested other ways to improve the sustainable process. The opportune rehabilitation for land occupation minimization besides adopting large-scale production to optimize the land used was endorsed (Ditsele and Awuah-Offei, 2012). In addition, coupling the remote sensing data with spatial and temporal land transformation analysis is recommended (Zhang et al., 2021). The exploitation of high ore grade should be the primary focus to mitigate the resulting environmental impacts (Zhang et al., 2021). Otherwise, in the case of exploitation of low-quality resources (i.e., quartz), an investigation of future mining and exploration technologies and different changes is highly recommended (Heidari and Anctil, 2022).

Other authors stressed the importance of replacing petrol processes to reduce fossil fuel depletion (Grbeš, 2016). Some other recommendations were concerning the system boundary in papers studying metals because of system expansion that includes coproducts and production technics. It will reveal that the principal coproducts contained in the junction with the metal are the main product destined for another market for these materials (Van Genderen et al., 2016). Indeed, integration of renewable energy to fuel the different processes is one of the repeated suggestions by the literature (Hong et al., 2018; Cenia et al., 2018; Farjana et al., 2019). As some of the papers assessed various technologies inside the mining and processing operations it was recommended to explore the adoption of heap leaching due to its intensive consumption of energy during long hours of operation (Cenia et al., 2018). Accordingly, promoting the energy efficiency and maintenance of electrical equipment to lessen fugitive emissions (Cenia et al., 2018). The LCA databases have also been a matter of debate as many authors reclaimed the absence of elementary flows and recommended the update of the impact category of land transformation in Ecoinvent to include the transformation from desert and burdens affecting its landscape (Issaoui, N.D.).

It is much encouraged to conduct more LCA studies on mining activities, especially in developing regions where LCI databases are still lacking and need more efforts to reduce uncertainties, since most of their secondary data is adapted from European/global databases. Sticking to transparency when describing every LCA step is one of the key parameters to help future researchers reuse and compare fairly the data and conclusions cited in the literature. Especially in LCA, the accurate definition of different information is significant. As mentioned earlier in this paper, assessing various scenarios concerning the phase of design in mining is crucial for diminishing the impact all along the supply chain. Otherwise, few papers tackled this subject which displays an opportunity for further work to fill this gap. Also, extending the spectrum of impact indicators should receive more attention than focusing only on the global warming indicator. This issue is observed in other fields and is not specific to mining due to worldwide mediatization. In addition, the energy transition that is excessively metal demanding cause soaring mining frequency. Still, to the best authors' knowledge, only very few

LCA studies has been conducted for lithium mining, for instance. This illustrates the big gap existing for studying such metals and minerals since only one study has been done for phosphate mining and beneficiation, even if it is one of the most demanded resources on earth. This urges us to dedicate more efforts to help the green transition, especially for energy-intensive mining activity.

- Breaking through the limits of traditional LCA: harnessing the potential of simulation and machine learning

To overcome the several challenges, researchers have increasingly explored the integration of machine learning and simulation tools into LCA. This subsection will discuss the role of simulation and machine learning tools in LCA and highlight recent advancements in the integration of these techniques.

Simulation tools, such as process simulation, environmental fate modelling, and impact pathway analysis, can be used to enhance the accuracy of LCA results and reduce uncertainties. Process simulation models can provide detailed information on the inputs, outputs, and emissions of a specific process. Environmental fate models can predict the fate and transport of pollutants in the environment, while impact pathway analysis can identify the potential environmental impacts of pollutants. This can consequently lead to improve the eco-conception and design for sustainability that would help achieve resource efficiency and stimulate the move away from a linear production and consumption system that follows a 'take-make-dispose' approach, and instead transition towards a circular one that promotes reuse and recycling (Abadías Llamas et al., 2019). Simulators like Outotec HSC has been proved by several authors to be effective and include the possibility to link with LCA databases as Gabi (Reuter et al., 2015). Furthermore, this approach enables optimization or modification of individual process steps and production methods to reflect the latest technologies and operating parameters, as well as the updating of emissions data to align with any changes made (Bartie et al., 2021).

Machine learning techniques, such as decision trees, neural networks, and random forests, can be used to handle large and complex datasets and automate data processing in LCA. By analyzing and learning from historical data, machine learning algorithms can improve the accuracy of LCA results and reduce uncertainties. For example, machine learning techniques have been used to develop models for predicting the environmental impact of products and processes based on their input–output data (Ghoroghi et al., 2022). The potential of forecasting the impacts at the design stage might be one of the powerful features of this synergy especially for guiding the decision-making process to achieve sustainability.

Recent studies have explored the integration of simulation and machine learning tools in LCA to improve its accuracy and efficiency. For example, researchers have developed a process simulation model to assess the environmental impact of a large system with more than 361 flows and 209 compounds (Fernandes et al., 2020). The model achieved a higher accuracy than traditional LCA methods and reduced the uncertainties in the results. Other studies have used environmental fate models and impact pathway analysis to estimate the potential environmental impacts of pollutants with a higher accuracy than traditional LCA methods (Boulay et al., 2011).

4. Conclusion

This paper reviewed 78 studies on the environmental impacts of minerals and metals mining using a life cycle assessment approach. The tendency was to use 1 t of commodity for minerals and 1 kg of commodity for metals. Most studies limited their system boundary from cradle to gate and relied on secondary data or completed data from other datasets to establish inventory. Simapro was the most used calculation tool, followed by Gabi and OpenLCA. ReCiPe and CML were the most used impact assessment methods in the mining industry.

The analysis of the four impacts (i.e., climate change, acidification, water consumption and land occupation) showed that those allocated to metals were higher while minerals mining had the lowest impacts per one tonne. For instance, gold has scored the highest impacts in GWP, AP, WD and LU at 2.65×10^5 kg CO2 eq, 2.29×10^5 kg SO_2 eq, 3.3×10^5 m3, 2.5×10^6 m2a respectively. Whereas the comparison based on annual production revealed a distinguished contribution of minerals compared to metals which is explained by its extensive production. During 2021, the global carbon footprint estimated showed that coal has the highest impact at 1.49×10^9 t CO_2 eq while Uranium has the lowest impact with 2.02×10^6 t CO_2 eq.

The limitations and recommendations included in this study were dedicated to emphasizing the existing gaps and provide opportunity for different aspects discussed in the literature to fulfil the intended accuracy and transparency. For instance, more studies are encouraged to tackle LCA of mining strategic metals and minerals for energy transition (i.e., lithium cobalt, etc.). Extending the system boundary to cover the whole life cycle will open-up opportunities for further reforms of this industry. Developing conversion factors is worth emphasizing giving their importance to enable benchmarking the results obtained globally and cumulate a solid unified knowledge globally. Moreover, it is imperative that LCA be utilized in conjunction with other technologies such as machine learning and simulation to explore new flowsheets and supply chains. This approach will facilitate the development of innovative solutions to close the loop of circular economy.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mineng.2023.108076.

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