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A review of the literature on the application of LCA methodology in the gold industry

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Abstract

Life cycle assessment (LCA) is a methodological approach frequently used to evaluate the potential environmental impacts of technological systems. This approach has reached a certain degree of development thanks to recent standardization work, however, several challenges remain, particularly in the minerals sector where life cycle assessment (LCA) still needs to be improved and expanded in its implementation. The main challenge of LCA is the difficulty of obtaining data to develop the life cycle inventory (LCI). The objective of this study was to develop a systematic review of the application of LCA in the gold industry. A total of 16 articles on gold mining were identified and discussed in the results and discussion section. In most of these studies, Simapro software was preferred as the life cycle assessment tool, and the ReCiPe method was used as the preferred impact assessment method in 56% of cases. Meanwhile, 44% of studies used the IMPACT 2002+, CML-IA, ILCD, LCA to ExLCA, DEC, CCR, EM-LCA, and Eco-Indicator 99 methods. Global warming, human toxicity, eutrophication, land use, partial water use, and metal resource depletion are the main impact categories assessed. Greenhouse gases and nitrogen compounds are substances emitted into the environment.

Keywords: LCA; Environmental sustainability; Gold mining; Sustainable development; Environmental assessment method

1. Introduction

The use of LCA began in industrial production systems in the 1970s, mainly to reduce energy consumption in the manufacture of plastics, steel, aluminum, and paper [1]. It was then extended to other sectors, such as the extractive industry. During the 1980s and 1990s, comprehensive models for assessing life cycle impact and calculating life cycle costs were introduced, and social LCA and consequential LCA gained ground during the first decade of the 21st century [2]. LCA has been disseminated worldwide thanks to standardization efforts by organizations such as the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC), the International Organization for Standardization (ISO), and more recently through the partnership between SETAC and the World Health Organization (WHO) [2]. After the first oil crisis and the creation of the European Commission's Directorate-General for the Environment, the standardization of LCA and the development of similar methods were mainly carried out in Europe due to the continent's high energy dependence.

In the 1980s, a new vision of development emerged following an in-depth assessment of the problems associated with industrial development, such as environmental pollution and overconsumption of fossil natural resources [3]. This

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concerns sustainable development. Environmental considerations became systematic in decision-making between 1987 and 1992. In order to study the use of natural resources and preserve the environment, techniques such as material and energy flow analysis (MEF), carbon footprint, and LCA were developed. Between 2000 and 2010, LCA underwent significant conceptual evolution. Numerous LCA studies were conducted and simplified methods were requested [3]. The European Commission was motivated to implement its Integrated Product Policy (IPP) in 2003, in which LCA and the life cycle approach became fundamental principles. In 2005, UNEP and SETAC launched the Life Cycle Initiative to create methods for characterizing impacts and then disseminate and harmonize methodologies [3]. During this period, demand for LCA studies increased. It is officially recognized as being multi-stage (it includes all stages of the life cycle, from the extraction of raw materials to waste or the recovery of components at the end of the product's life) and multi-criteria (it assesses various impacts such as global warming).

Although the ISO standard defines LCA and provides a general framework for conducting an assessment, it leaves interpretation up to practitioners [4]. This has led to differences in how the impact of an LCA is assessed. LCA is a very comprehensive method because it includes all relevant processes related to the function that the product or service provides. In addition, it allows for a broad consideration of potential environmental impacts related to inputs from the environment (resource extraction) and outputs emitted into the environment (air, water, and soil emissions) [5]. The life cycle of a product, from the acquisition of raw materials to its production, use, end-of-life treatment, recycling, and disposal (from cradle to grave), is addressed in LCA. It covers environmental aspects and potential environmental impacts (resource use and environmental consequences of emissions) [6]. Therefore, the main objective of LCA is to quantify the environmental effects of a product or product system throughout its life cycle.

Life cycle assessment (LCA) is a relatively new method that can be used to objectively evaluate the environmental impact of various activities, products, and processes. LCA covers the successive and interconnected stages of a product or process system, from the acquisition or production of raw materials from natural resources to final disposal [7]. Many of the most recent developments have been initiated to expand traditional environmental LCA to a more comprehensive life cycle sustainability assessment (LCSA). LCA is evolving toward LCSA, which is a framework for transdisciplinary integration of models rather than a model in itself. LCSA uses a plethora of disciplinary models and guides the selection of appropriate models based on a specific sustainability issue. The main challenge is to structure, select, and make available the plethora of disciplinary models according to different types of life cycle sustainability issues [2]. LCA is carried out in four stages: defining the objectives and scope of the study, while defining the functional unit; life cycle inventory; impact assessment and interpretation of results (see Figure 1).

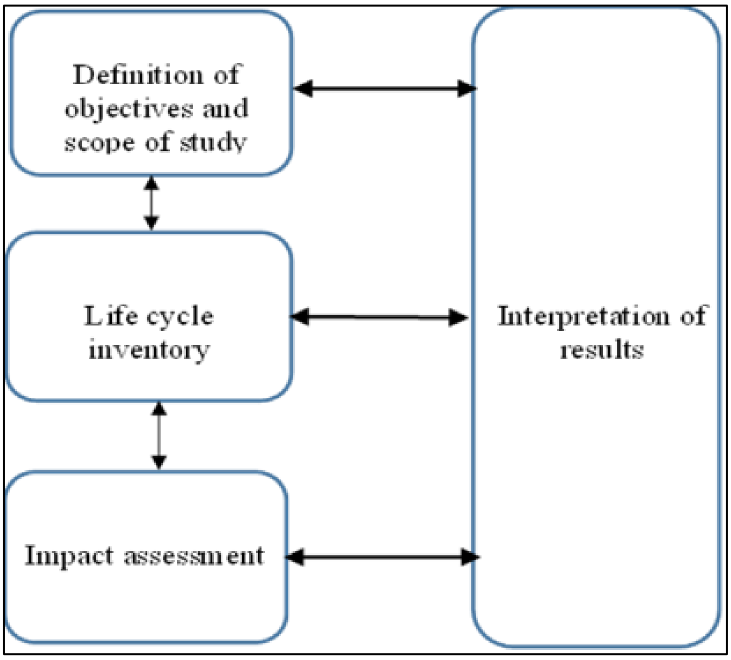

Figure 1 Main steps of life cycle assessment [11]

A series of LCA studies have been conducted in the gold industry by researchers and mining companies with the aim of assessing the environmental impacts of gold production using a cradle-to-grave, cradle-to-gate, or gate-to-gate approach. Each of these studies has demonstrated the applicability of the LCA methodology in the gold industry. They have produced good results which, depending on the case, have enabled the selection of the best production technologies or the identification of strengths and weaknesses in order to guide decisions for improvement from an environmental perspective [8], [7], [9]. The results of life cycle assessment (LCA) vary from one standardized LCA method to another, from one simulation software program to another, and from one mining metal to another [10].

However, most studies such as [12], [13], [14], [15] have focused on the refining, enrichment, and processing of gold ore without taking into account in detail the different phases of mining due to the unavailability of data to develop the life cycle inventory. Essential details of the mining process that affect the final environmental impacts are rarely taken into account, such as : exploration and development work, the extraction method used, production, ore loss, location, and factors depending on the extraction and processing method that govern the nature of environmental discharges are the most significant omissions [9]. Furthermore, only the studies by [16] in Guinea and [17] in Côte d'Ivoire considered the entire life cycle from exploration to post-mining. In addition, each author assessed the impacts using an ideal LCA method such as : ReCiPe 2016, 2013, 2009 ; ILCD, DEC, and Impact 2002+; EM-LCA, CML, etc., in various software programs such as Simapro, GaBi, GaBi combined with HSC Sim software, Arc GIS, OpenLCA, etc., using databases such as EcoInvent, ELCD, etc…

1.1. LCA limit

The limitation of LCA studies is the difficulty of compiling a life cycle inventory (LCI) due to a lack of data. Data availability is a major concern in LCA studies, as most of the high-quality data required for this work is confidential to companies. Little information is available in the public domain in a format suitable for LCA [9]. The use of generic information means that LCA studies are unable to adequately address site-specific impacts and therefore capture the true spatial and temporal dimension of life cycle impact assessment (LCIA) results [9]. There are Ecoinvent-licensed databases that are integrated into commercial software [18].

There are LCA datasets in other databases such as ELCD Bottles and Agribalyse that are included in the free OpenLCA software. However, these databases are incomplete because there is a lack of data related to the mining industry. It has also been noted that the majority of LCA studies are carried out in developed countries such as Europe, China, Japan, North America, and Australia. However, in Latin America and Africa, the number of scientific publications on LCA is very limited, if not non-existent, with the exception of Brazil and South Africa [19]. In West Africa, scientific publications on LCA are also beginning to appear, specifically in Côte d'Ivoire, such as the studies by [17], [20] and in Guinea [16]. The objective of this review is to identify articles on the application of LCA in the gold industry in order to identify the main mining processes and factors contributing to the environmental impacts of gold mining. It then examines the categories of impact assessed and the different methods and software used to evaluate these impacts. To achieve this, we systematically reviewed 16 articles in which the various characteristics mentioned above are identified.

This paper is structured in three main parts : the first part presents the introduction, which sets out the context of the study and presents some studies on the application of LCA in the mining industry, its importance, and its challenges ; the second part outlines the method used in this study ; and the third part presents the results and discussion. Finally, a conclusion with recommendations for optimizing life cycle inventories and reducing the environmental impacts of gold mining will conclude this study.

2. Methods

A systematic review was conducted on LCA studies in the gold industry to gain insight into the selection of recent publications in this field. This selection is based on the system boundaries, functional unit, and life cycle inventory (LCI) of the LCA studies. This work focuses primarily on articles published in the field of gold mining. Therefore, newly conducted LCA studies on gold products are included in this field of study. Thus, absolute priority was given to publications that focused on gold mining and gold ore processing. All of these studies list the different categories of environmental impact per unit of mass of the mineral product (ore concentrate and metal contained in the gold ore concentrate). To ensure the accuracy of the information and opt for a clearer method, we used specific databases such as Science Direct, Google Scholar, Springer, the Journal of Cleaner Production database, Elsevier, and the International Journal of Life Cycle Assessment database for this review. Databases such as Science Direct, Google Scholar, and Springer are recognized for their credibility, scope, and volume of articles published in the environmental sector. Science Direct offers a comprehensive selection of academic works [21], according to [22].

3. Results

This section presents the bibliometric results and trends observed in the field of publishing, the main characteristics of the life cycle, and the different methods used in the selected publications. Following implementation of the review protocol and as part of the selection process, 56% of case studies applied the ReCiPe method, while 44% of studies used the IMPACT 2002+, CML-IA, ILCD, LCA to ExLCA, DEC, CCR, EM-LCA, and Eco-Indicator 99 methods. Table 1 illustrates the main characteristics of the LCA studies inventoried on gold.

Table 1 Main characteristics of the inventoried LCA studies on gold

Réf. No	Réferences	Journals	Assessment method	Functional unit	Phases de l'exploitation aurifère	Data base	Software used
1	(Konaté et al., 2025b)	IJIAS	ReCiPe 2016, IMPACT 2002+ and CML-IA	46t	Exploration to post-mining	ELCD	OpenLCA
2	(Chen et al., 2021)	Ecological Indicators	ReCiPe 2016	1t	Operation	LCI	Simapro 8.3
3	(Farjana and Li, 2021)	Resources, conservation and recycling	ILCD	1kg	Operation	EcoInvent 3.6	Simapro 8.5
4	(Cano et al., 2020)	The International Journal of Life Cycle Assessment	LCA and ExLCA	1kg	Operation	EcoInvent 3.1	ArcGIS
5	(Elomaa et al., 2020)	The International Journal of Life Cycle Assessment	ReCiPe 2016	1kg	Operation	EcoInvent 3.5	GaBi and HSC Sim.
6	(Fritz et al., 2020)	The International Journal of Life Cycle Assessment	ILCD	1kg	Operation	Ecoinvent 3.5	GaBi
7	(González-Campo et al., 2020)	The International Journal of Life Cycle Assessment	ReCiPe 2014	2,17E+08g	Operation	EcoInvent	Simapro 2.8
8	(Islam et al., 2020)	Resources, Conservation and Recycling	ReCiPe 2009	1kg	Operation	EcoInvent	ArcGIS 10.4
9	(Cano Londoño et al., 2019)	Ecological Indicators	EM-LCA and Ecoindicador 99,	1kg	Operation	EcoInvent	OpenLCA
10	(Farjana et al., 2019)	Science of The Total Environment	ILCD, CCR, DEC and impact 2002+	1kg	Operation	EcoInvent	Simapro 8.5.

11	(Martínez et al., 2019)	Journal of Cleaner Production	ReCiPe 2000	$1m^3$	operation	EcoInvent	OpenLCA
12	(Chen et al., 2018)	Journal of Cleaner Production	ReCiPe 2009	1kg	Operation	EcoInvent	Simapro
13	(Yao, 2018)	HAL Open Science	ReCiPe 2016	1kg	Exploration to post-mining	Ecoinvent	Simapro 8.3.0.0.
14	(Haque and Norgate, 2014)	Cleaner Production Journal	ReCiPe 2016	1kg	Operation	Ecoinvent	Simapro
15	(Yahaya, 2012)	Iranica Journal of Energy & Environment	Eco-Indicator 99	1kg	Operation	Ecoinvent	Simapro
16	(Ingwersen, 2011)	U.S. Environmental Protection Agency	DEC and ExLCA	1g	Operation	Ecoinvent v2.0	SimaPro 7.1

[16] conducted an LCA to assess the potential environmental impacts of gold production at the Kiniéro mine in Guinea, taking into account all phases of the mine's life cycle. The ReCiPe 2016 method was used with OpenLCA 1.11.2021 software in the ELCD database to assess several impact categories. The functional unit was 46 tons of gold produced. The results showed that transportation, electricity generation, and gold ore processing during the mining phase are the main contributors to Kiniéro's environmental impact. Greenhouse gases and nitrogen compounds are substances emitted into the environment. Global warming (89%), fine particle formation (69%), human carcinogenic toxicity, aquatic eutrophication and depletion of metal resources (100%), and water use (75%) are the impact categories identified.

[12] conducted an LCA to assess the availability of water footprint with a UF of 1 ton of gold produced in China. Water scarcity, carcinogenic and non-carcinogenic substances, freshwater ecotoxicity, aquatic eutrophication, and acidity are impact categories assessed by the ReCiPe.2016 method using Simapro 8.3 software in the LCI database. The functional unit was 1 t of gold produced. The results showed that carcinogenic and non-carcinogenic substances are the main contributors to damage to human health, with respective values of 3.88∗10-7case and 1.17 ∗10-6 case ; while freshwater ecotoxicity : 2.35∗10-3PAF.m3.d is responsible for damage to ecosystem quality. The other categories have the Following values: aquatic eutrophication: 1.64∗10-3kg PO3-eq; acidification: 0.21 kg SO42- eq and water scarcity: 0.16 m3 deprived; human health: 7.73∗10-6 DALY and ecosystem quality: 6.78∗10-6 Species.yr. The application of hydroelectricity and biodiversity processes would reduce the effects of carcinogenicity, aquatic eutrophication, acidification, water scarcity, freshwater ecotoxicity, human health, and ecosystem quality by 17.17%, 20.23%, 66.64%, 18.16%, 42.59%, 27.56%, and 5.81%.

[23] conducted an LCA in Colombia with the aim of comparing the sustainability of an open-pit mine and an alluvial mine. Cumulative Energy Demand and Exergy methods were used to identify the renewable and non-renewable energy used in the process. The results showed that 53% of the energy consumed in the open-pit mine comes from fossil fuels and 26% from water energy use, while 94% of the energy flow in the alluvial mine comes from water used as a resource in ore processing. According to the authors, to reduce the environmental impact of these mines, efficiency must be increased by reducing the energy required in tailings, in the open-pit mining process, in the casting stages, and in the molding of alluvial mining. Emissions in both mines must be reduced. Renewable energy such as solar, wind, and hydraulic energy must be used. Finally, practice the concept of a circular economy, which reduces resource consumption.

[13] conducted an LCA study to compare cyanide-based and cyanide-free (halogen-based) gold leaching processes, using a functional unit of 1 kg of gold produced. Environmental impacts such as global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and water depletion were assessed using the ReCiPe 2016 method with GaBi software combined with HSC Sim software. The results showed that the PRP of the halogen process is higher than that of cyanidation, with respective values of PRP = 12.6 t CO2 eq/kg Au and PRP = 10 t CO2 eq/kg Au. This means that the halogen process has a greater impact on global warming than cyanidation. The main contributor to

this increase is the calculation of the footprint linked to the units of gold produced. Gold recovery by cyanidation is 98.5% and 87.3% by the halogen process. The extraction of gold from the wash water in the halogen process yields 98.5% of the gold, reducing the PRP to 11.5 t CO2-e/kg Au.

[24] conducted a Life Cycle Assessment (LCA) to evaluate the environmental footprint of gold from gold waste recycling in Germany. The functional unit was defined as equivalent to one kilogram of recycled gold. Various impact categories such as land use, human carcinogenic toxicity, and global warming were analyzed using the ILCD method with GaBi software and the ecoinvent v.3.5 database. The heavy use of chemicals is the main factor contributing to carcinogenic toxicity for humans. The results indicate a cumulative energy demand (CED) of 820 MJ and a global warming potential (GWP) of 53 kg-CO2-Eq. per kilogram of gold. In comparison, standard datasets show direct energy consumption (DEC) and global warming potential (GWP) levels of approximately 8 GJ and 1 t-CO2-Eq. per kilogram of gold, respectively, for e-waste recycling, while the corresponding levels for mining are 240 GJ and 16 t-CO2-Eq. per kilogram of gold. In conclusion, the results indicate that sourcing gold from precious metal recycling facilities that adhere to strict technological standards and guarantee the reliability of the origin of recycled materials is approximately 300 times more cost-effective than primary extraction.

[25] conducted an LCA of a large-scale gold mine in Peru with the aim of assessing the mine's environmental impacts. With a functional unit of 2.17E+08g of gold produced, the ReCiPe method was used to assess the impacts using SimaPro software. The main categories identified were climate change, agricultural land use, and depletion of water resources (2.2%) and metals (2.2%). In addition, impact categories such as marine ecotoxicity at 63%, freshwater ecotoxicity at 92.9%, and terrestrial ecotoxicity at 89% revealed a potential positive impact on the environment. The analysis showed that the main contributors to the environmental impact are the leaching and ore processing processes.

[26] conducted a comparative LCA of the environmental sustainability of two gold production methods with the aim of assessing the sustainability of an open-pit gold mine and an alluvial gold mine using the emergy analysis method and the combined emergy and life cycle assessment (EM-LCA) method. The results of the analysis indicate that the open-pit and alluvial mines have emergy sustainability index values of 0.02 and 0.04, respectively, using emergy compatibility, and 0.002 and 0.035 using EM-LCA. This means that both mines are unsustainable because the indices are below 1. However, Emergy sustainability index values < 1 indicate unsustainable practices, indices between 1 and 5 indicate medium-term sustainable practices, and values above 5 are considered sustainable. The results also show that the low value of open-pit mines is linked to the high emissions generated by these mines, which depend on industrial processes that consume significant amounts of non-renewable resources. The authors show that the use of the new EM-LCA approach has the potential to extend emergy analysis to incorporate emissions.

[10] conducted an LCA on copper, gold, lead, silver, and zinc products. The objective of the study was to assess the environmental impacts of the enrichment process for these metals using a functional unit of one kilogram of each metal. Fifteen impact categories were assessed using the ILCD, CCR, DEC, and Impact 2002+ methods using Simapro 8.5 software. The results showed that the impact on ionizing radiation for gold enrichment is 2148.9 KBq U235 eq. The impact on terrestrial eutrophication is 172.22 kg NMVOC eq. The acidification potential is 0.019 UTC. The non-carcinogenic effects of human toxicity are estimated at 3.88 E-04 UTCh. The carcinogenic effects of human toxicity from gold enrichment are estimated at 2.37 E-05 UTCh. Coal consumption generates 15,431 MJVLH of heat, while the smallest amount of heat comes from gas, with 8,903 MJVLH. This means that gold enrichment is the main contributor to environmental impacts. The authors have shown that integrating renewable energy methods could reduce the environmental impacts of mining these metals.

[27] conducted an LCA at a Cu-Ag-Au mine in Laos, Southeast Asia. The objective was to quantify the environmental impacts of this mine using remote sensing based on global warming potential (GWP) and gross energy requirements (GER). With a functional unit of 1 kg of Cu, impact categories such as greenhouse gases (GHG), global warming potential (GWP), and gross energy requirements (GER) were assessed using the ReCiPe 2009 method with ArcGIS 10.4 software. The results showed that CO2 emissions from mining and processing were 0.008058 kg and a total GWP of 3.4 kg CO2 eq/kg Cu. The results also show that fossil fuel use contributes 40% to the GWP. The authors showed that replacing the electricity from the Chilean national grid used for copper ore processing with solar and hydroelectric power would reduce GWP emissions by more than 60-70%.

[28] conducted an LCA of a passive remediation system for acid mine drainage (AMD). The functional unit was one cubic meter of treated water, and eleven impact categories were assessed using the ReCiPe H.1.11 Europe 2000 method with OpenLCA software. Among these 11 categories, the relevant impact was climate change (0.00017 hbt/year to 3.4 hbt/year) per year of AMD treatment. The global warming potential (GWP) impact is 1.86 kg CO2 eq/m3, with carbonate dissolution contributing 94% (1.74 kg CO2/m3).

[15] conducted an LCA study to assess the environmental impacts of gold production in China, using a functional unit of 1 kg of gold. Several impact categories were assessed using the ReCiPe 2009 method with Simapro software. The results also showed that for a base ore grade of 3.5 g Au/t ore, the environmental footprint of gold production, based on the life cycle, was estimated at approximately 200,000 GJ/t Au, 18,000 t CO2eq/t Au, 260,000 t water/t Au, and 1,270,000 t solid waste/t Au for non-refractory ore. Mining and crushing are the main contributors to the greenhouse gas footprint. Electricity is the main factor responsible for just over half of the greenhouse gas footprint. The authors concluded that extraction and grinding are the main contributors to the environmental impact.

[17] conducted an LCA to assess the potential environmental impacts of the Afema gold mine in Côte d'Ivoire, taking into account all phases of the mine's life cycle. The ReCiPe 2016 method was used in Simapro 8.3.0.0 software to assess several impact categories based on a functional unit of 1 kg of gold. The results showed that the main contributor to environmental impact is the mining phase. Off-site impacts are the most significant on human health at 90%, compared to 2% for on-site impacts and 98% versus 2% for ecosystem quality. On-site impacts are significant in terms of resource depletion at 81%. The main contributor to the deterioration of ecological quality is climate change at 70%, followed by land transformation and occupation at 23.2%. The main contributor to resource damage is the depletion of metal resources at 90%.

An LCA was conducted by [29] on traditional gold mining and urban gold mining. The objective was to assess and compare the environmental impacts of crushing and grinding processes based on electricity consumption. The functional unit was 1 kg of gold produced. Approximately 50-65% of the total electricity was used in the grinding process. Several impact categories, such as human toxicity carcinogens, respiratory organic and inorganic compounds, radiation, climate change, ozone layer, ecotoxicity, acidification or eutrophication, land use, and minerals, were assessed using the Eco-Indicator 99 method with SimaPro software. The results showed that crushing and grinding from traditional mining had the greatest environmental impact, with a single score of 399 Pt compared to urban mining, with a score of only 1.81 Pt. In both cases, the greatest impact is on human health. Electricity consumption is responsible for the damage to human health.

[30] conducted an LCA to assess the environmental impact of gold production from refractory and non-refractory ore from mining to refining. Intrinsic energy, greenhouse gas emissions, intrinsic water, and solid waste load are assessed based on a functional unit of one ton of gold. The results showed that emissions from refractory ore are 50% higher than those from non-refractory ore due to the additional input of materials and energy, as well as gold and silver losses during additional processing.

[31] conducted a life cycle assessment using Emergie as a criterion for evaluating the environmental impact of a large gold mine in Peru. The aim was to assess the total environmental impact associated with the production of gold and silver bullion at the Yanacocha mine in Peru. The operational unit corresponded to 1 gram of gold produced. The results showed that the total energy required for all life cycle stages associated with the production of one gram of gold is estimated at approximately 6.8×10^{12} sej, with an approximate confidence interval of 6.2×10^{12} (x÷) 2.0. The main components of the mine's overall energy consumption include chemicals (42%), fossil fuels (32%), and electricity (14%). Equipment, such as mining infrastructure and lifting devices, accounts for 5% of the total. The findings highlight the importance of emergy in the context of Life Cycle Assessment (LCA). In conclusion, the authors suggest using Emergy as an indicator of overall resource exploitation in the context of life cycle assessment (LCA). It is the most relevant measure for assessing the long-term environmental sustainability of gold production.

Each of these studies demonstrated the applicability of LCA methodology in the mining industry. The results were satisfactory, enabling the selection of the best production technologies or the identification of strengths and weaknesses to guide environmental improvement decisions (Haque and Norgate, 2014 ; Norgate and Haque, 2010 ; Reid et al., 2009 ; Durucan et al., 2006). In addition, each author assessed the impacts using an ideal LCA model. The results of the analysis also revealed that 56% of publications opted for the ReCiPe method to assess environmental impacts, while the remaining 44% used other methods (see Fig. 2). This shows that the ReCiPe method is the most widely used. This high usage is justified by its reliability and the large number of substances it takes into account. ReCiPe takes into account 53,655 substances. It covers a series of 18 impacts categories at the intermediate level and 3 at the final level. Other methods take fewer substances into account and cover fewer impact categories to be assessed. IMPACT 2002+, for example, takes into account 11,751 substances and covers a series of 15 impact categories at the intermediate level and 4 at the final level. CML-IA, which is an intermediate method, takes into account 3,944 substances and covers 11 impact categories at the intermediate level.

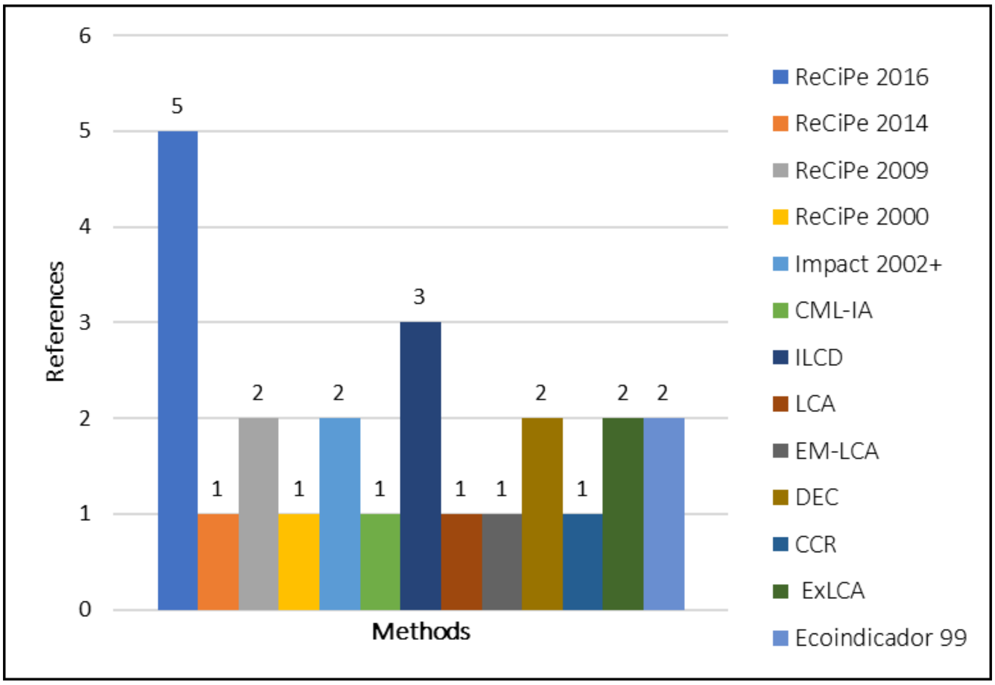

Figure 2 LCA methods applied in the selected studies

4. Conclusion

The objective of this review was to identify articles relating to the application of LCA in the gold mining sector, with the aim of identifying the major processes and factors contributing to the environmental impacts associated with gold mining. Subsequently, the impact categories examined and the various methods and software used to carry out this assessment were presented. According to this study, it appears that transportation, electricity generation, ore processing, and greenhouse gas and nitrogen compound emissions are the main processes and factors contributing to the environmental impacts associated with gold production. In addition, the major impact categories identified in the various studies examined include climate change, human toxicity (both carcinogenic and non-carcinogenic), eutrophication of aquatic environments, ecotoxicity, depletion of metal resources, and land use. Simapro software was mainly used as a life cycle assessment tool. The results of the analysis reveal that 56% of publications opted for ReCiPe to assess environmental impacts, while the remaining 44% used other methods.

The design phase of a mining project represents a significant opportunity to improve environmental sustainability, as decisions made at this stage can greatly influence the long-term performance of mining operations. In addition, the available data is more limited, which increases the complexity of decisions at this stage of the project due to a limited number of options and uncertainties. Improvements can also be made during the operational phase, and although the impact of decisions made at this stage is likely to be less significant, it is possible to discover unexpected potential environmental benefits as part of the holistic approach to dedicated public transport lanes (TCSP). Despite the significant progress made on site, major problems remain. For example, inconsistencies have been identified in the definition of the functional unit and in the system's limitations (temporal and technological). While climate change has been widely studied as the main environmental issue, the consequences of water use and waste management have often been underestimated in the scientific literature.

Recommendation

In order to conduct a more effective LCA in a gold mining company, taking into account the quantity and quality of the data required and the difficulty of obtaining data to carry out this study, we call for closer collaboration between mining companies, the government, researchers, and students in order to provide more accurate and relevant data. We recommend that mining companies make data on mining activities available to the government. It is also up to the government to make this data accessible to researchers. In addition, the implementation of LCA methodology in mining companies in Africa is currently being developed, as environmental impact assessment is moving towards eco-design. Eco-design consists of integrating environmental preservation into EIAs from the design stage of any project, product, or service. To this end, the creation of databases containing assessment methods adapted to African circumstances in free or low-cost software would help to avoid uncertainty in the results obtained. To achieve this, data collection at specific times will simplify the implementation of African databases. On the other hand, to reduce greenhouse gas (GHG) and volatile organic compound emissions in mining industries, it would be preferable to favor the use of renewable energy, such as replacing diesel in transportation with biodiesel and generators with wind power, solar photovoltaic energy, and biomass for electricity production.

Compliance with ethical standards

Disclosure of conflict of interest

This article presents no conflict of interest, and the authors are free to publish their work in this journal.

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