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Examining the environmental impact of mining activities using life cycle assessment (LCA): A case study of the Kiniero gold mine (Semafo) in Guinea

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ABSTRACT: This study examines the environmental impact of gold mining activities, particularly focusing on the Kiniero Gold Mine in Guinea. Utilizing Life Cycle Assessment (LCA) methodology, the study evaluates potential environmental impacts from exploration to post-mining phases. Seven impact categories are assessed using ReCiPe 2016 H, CML-IA, and IMPACT 2002 + methods via OpenLCA 1.11 2021 software. These categories include particulate matter formation, global warming, non-carcinogenic human toxicity, land use, aquatic eutrophication, metal resource depletion, and water consumption. Findings reveal that the exploitation phase has the most substantial environmental impact, notably through greenhouse gas emissions, primarily Carbon dioxide (90%), Methane (9%) and Nitrogen monoxide (1%) from diesel combustion. Metal emissions into water contribute significantly to non-carcinogenic human toxicity, while aquatic eutrophication is mainly attributed to nitrogenous nutrient emissions from gold ore processing (N: 76%, NH_4^+: 15%, NO_3^-: 6% and NH_3: 3%). Climate change emerges as the most significant impact, equivalent to the impact of three individuals annually compared to other impacts. To mitigate these effects, reducing GES emissions by replacing diesel with biodiesel in transportation and promoting renewable energy for electricity production is suggested. Applying LCA facilitates environmentally sustainable mining practices, preserving ecosystems, and mitigating climate change risks.

KEYWORDS: Openlca, Environmental Impact, LCA, Mining Activities, Semafo-Guinea.

1 INTRODUCTION

The mining industry contributes to the development of countries by creating jobs and reducing unemployment [1]. Guinea is one of Africa's leading gold-producing countries. However, gold mining is having a growing impact on the environment by altering ecosystem functioning, such as land and water degradation and biodiversity loss, leading to global warming. Global warming causes heat waves, drought, flooding and changes in the behavior of aquatic species. It is caused by the emission of greenhouse gases into the air, such as CO_2, CH_4, etc.

The gold industry also consumes a great deal of water and chemicals during the processing of gold, and generates large quantities of waste. These wastes and chemicals, such as metal compounds (Hg, Pb, As and Cd), can end up in the environment. Metal pollution is a major concern for regions around the world seeking to preserve their environment [2].

This concern affects the sub-prefecture of Kiniéro, located 650 Km east of Conakry (Guinean ca-pitale), where numerous mining activities have been developed since 2002. These mining activities take the form of various gold panning sites and a gold mine called Semafo (Société d'Exploration Minière de l'Africaine de l'Ouest).

At Semafo-Guinée, the mine is open-pit, and the gold ore is processed using the carbon cyanidation process, also known as CIL (Carbon in-Leach). Hundreds and thousands of tonnes of rock are extracted to ensure planned production of 46 t of gold ore per hour. However, the environment is affected by every stage of ore extraction, physical and chemical processing. To assess the impact of pollutants at Semafo, several studies have been carried out, such as those by [3], [4], [5]. All these authors have applied the Environmental Impact Assessment (EIA) method. EIA is a commonly used method, as required by regulations. However, it does not impose any specific impact assessment method, and is limited to impacts generated within the perimeter studied, known as direct impacts or onsite impacts. It does not consider impacts linked to land use or energy consumption.

On the other hand, the current challenge is to reduce pollutant emissions. To meet this challenge, LCA is the ideal method, as it considers not only direct impacts, but also indirect or of-site impacts. In addition to the method required to assess environmental impacts, it enables the adoption of appropriate measures to reduce pollutant emissions. Given that LCA has never been applied in Guinea or at Semafo, we set ourselves the main objective of applying LCA as an alternative method for assessing the potential environmental impacts of the Kiniéro mine's life cycle.

LCA is both a decision-making tool and a powerful method for assessing the potential environmental impact of a product, product system or project during its life cycle, by quantifying all inputs such as material use and energy consumption from the technosphere, and all outputs such as pollutant emissions and waste production on the environment or ecosphere. A number of studies have been carried out on the life cycle assessment of mid-industry operations, including the results of a few such as [6], [7], [8], which obtained data on human toxicity, water use, aquatic eutrophication and so on. All these studies have proven the applicability of LCA methodology in the mining industry.

2 Material And Methods

2.1 Study Area

The Kiniéro or Semafo gold mine is located in the Kiniéro sub-prefecture, five kilometers (5 km) north of Kiniéro-centre. The Kiniéro sub-prefecture is located in the southeast of the Kouroussa prefecture in the Kankan region of Upper Guinea in northeastern Guinea. It was operated by a Moroccan company called SEMAFO (Société d'Exploration Minière de l'Afrique de l'Ouest), from 2002 to 2014. The mine is located between 10°30' and 10°20' north latitude and 9°50' and 9°40' west longitude. It covers an area of 25 km2. This concession has been reallocated to the British company Sycamore mining, which has replaced it over an area of 450 km2. The minerals mined are oxides and sulfides [5].

The climate in the study area is sub-Sudanese. It is characterized by abundant rainfall, with more than 1,600 mm3 per year. August and September are the rainiest months. The maximum temperature is around 40°C and the minimum is around 15°C. The region experiences two types of air masses: monsoon and trade winds. The region has four types of vegetation: herbaceous, shrubby, arborescent and forest. The terrain is predominantly plateau, with the majority of the site and its surroundings at an altitude of 400-450 meters. The study area is characterized by two contrasting seasons: a dry season from November to May, and a rainy season from May to October. Nearly 50% of the population is involved in gold panning [5].

2.2 Data Collection Material

The LCA is carried out in 4 stages: Definition of objectives and scope of study, Life Cycle Inventory, Impact assessment and Interpretation of results.

2.3 Definition Of Objectives And Scope Of Study

Defining the objectives and scope of the study is an important step in LCA, as it defines the objectives of the study, the boundaries of the system under study and the functional unit (FU), the quantitative measure of the function under study, on the basis of which the impacts are calculated.

2.4 Objectives And Functional Unit Definition

2.4.1 Definition Of Objectives

The aim of this study is to carry out the first LCA in Guinea to assess the potential environmental impacts of gold production at Semafo-Guinea during its life cycle, from the exploration phase to the post-mine phase.

2.4.2 Functional Unit

The functional unit (FU) is the quantitative measure of the function under study. It is a reference that standardizes all the inputs and associated outputs of a system under study. In our study, the functional unit (FU) chosen is 46 tonnes of gold ore produced per hour. The system boundary covers the raw materials and energy involved in the gold ore extraction process, from leaching to the 46 t/h production rate (Figure 1).

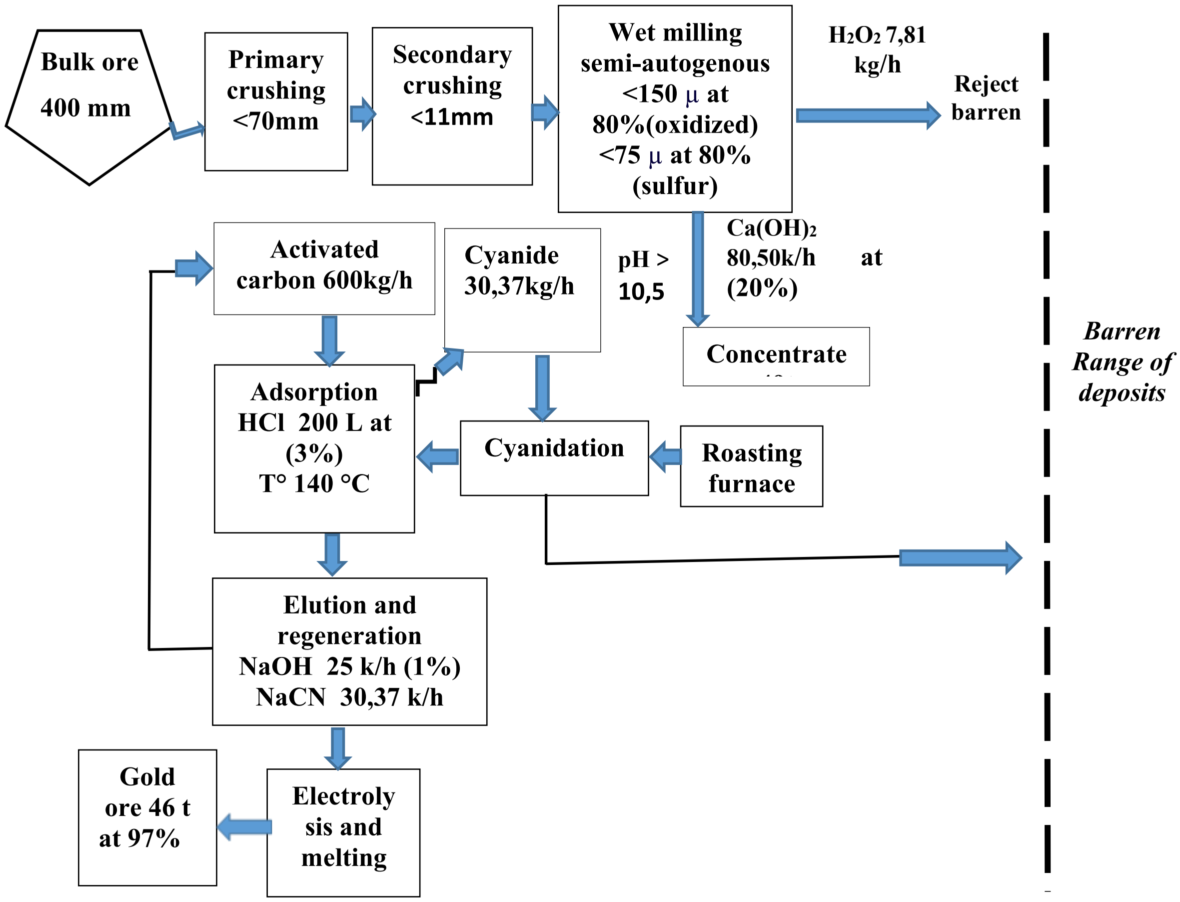

Fig. 1. System Boundary

2.4.3 Life Cycle Inventory

The life-cycle inventory consists of collecting input and output data for modeling purposes. To carry out the mine life-cycle inventory, we conducted a month-long staff survey to obtain documentation on the mine. Inventory data were collected on the basis of primary and secondary data. The primary data came from the mine's environmental impact assessment reports. They include input data such as the mine plan, chemicals used in ore processing such as chlorhydric acid (HCl), cyanide (CN), lime (Ca (OH) $_2$), hydrogen peroxide (H_2O_2), soda ash (NaOH), ammonium nitrate ($NH4NO_3$), fuel (diesel), activated carbon, electricity, land area occupied, machinery, water used and ore extracted, come from the study by (Sycamore mining, 2020; Cissé, 2005). And output data such as substances emitted into water and air, like nitrate (NO3-), ammonium (NH4), etc., and greenhouse gases such as carbon dioxide (CO_2), sulfur dioxide (SO_2), nitric oxide (NO), methane (CH_4) also come from the study by [5]. Missing secondary or information data come from the literature. They concern waste treatment data taken from work carried out by [6]. Construction data (materials, machinery, etc.) from work by [9]. The mine life cycle inventory data are presented in Table 1.

Table 1. Life Cycle Inventory of the Studied System (functional unit 46 t of ore produced)

Flux		Quantity	Unit
Inputs			
Calcium hydroxide		80.50	kg /h
Diesel		18 040	Kg
Electricity		2090	kWh
Excavator		8 360	Kg
Explosive		500	Kg
Hydrochloric acid		200	Kg/h
Peroxide		7.81	kg /h
Mining site occupation		160000	m^2
Oxygen		0.3	Kg
Ore mined		49	T
Process water		2662000.0	Kg
Sodium cyanide		30.37	kg /h
Activated carbon		600	kg /h
Sodium hydroxide		25	kg /h
Temperature		140	°C
Ore transport		228.8	t*km
transport of barren		44.8	t*km
wastewater - untreated End-of-life treatment/Wastewater treatment		7.01	Kg
Outputs			
Arsenic	emission to groundwater	1.0E-9	kg
Cadmium	emission to groundwater	1.0E-9	kg
Calcium	emission to groundwater	5.2E-5	kg
Carbon dioxide	emission to air	42880.2	kg
Chloride	emission to groundwater	5.0E-5	kg
Chromium	emission to groundwater	1.0E-9	kg
Cyanide, sodium	emission to groundwater	1.0E-8	kg
Untreated wastewater	emission to river water	2.89 E-2	kg
Waste oil	emission to river water	1200	kg
Lead	emission to groundwater	1.0E-9	kg
Magnesium	emission to groundwater	2.5E-5	kg
Mercury	emission to groundwater	1.0E-9	kg
Nitrate	emission to groundwater	8.0E-7	kg
Nitrogen monoxide	emission to air	4.2	kg
Potassium	emission to groundwater	1.2E-5	kg
Sulphate	emission to groundwater	3.2E-5	kg
Sulphur dioxide	emission to air	2.37	kg
Arsenic	emission to river water	2.0E-8	kg
Cadmium	emission to river water	2.0E-9	kg
Calcium	emission to river water	1.6E-5	kg
Chloride	emission to river water	5.8E-5	kg
Chromium	emission to river water	5.0E-9	kg
Cyanide, sodium	emission to river water	5.0E-9	kg
Lead	emission to river water	2.0E-8	kg

Magnesium	emission to river water	1.5E-5	kg
Mercury	emission to river water	5.0E-9	kg
Nitrate	emission to river water	4.5E-6	kg
Potassium	emission to river water	4.15E-6	kg
Sodium	emission to river water	3.749E-5	kg
Sulphate	emission to river water	2.3E-5	kg

2.4.4 Life Cycle Impact Assessment

Impact assessment consists of transforming all the data listed in the life cycle inventory into potential environmental impacts. This process is known as life cycle impact assessment. To assess the environmental impacts of the mine's life cycle, we inserted all the inventory data into OpenLCA 1.11 2021, then used the RéCiPe 2016 H method as the main assessment method, accompanied by the IM-PACT 2002+ and CML-IA methods to assess the mine's life cycle impacts. Finally, the results obtained were normalized. Normalization consists in assessing the relative contribution of the system studied to a particular impact. It is obtained by dividing the results for each impact category by the number of inhabitants in the study area (Formula 1).

$$Résultat\ Normalisé_{cat} = \frac{Résultat\ cat}{Nht} \quad (1)$$

3 Results

3.1 Analysis Of Contributions From Various Phases To Impact Categories Identified At The Midpoint Level

The figure 2 presents the outcomes detailing the overall impact contribution of each phase of the mine on the determined impact categories at the midpoint level. It highlights that the operational phase predominantly influences Semafo's gold production's total environmental impact. Specifically, concerning fine particulate formation, operations contribute 69%, development 20%, exploration 7%, and post-mining 4%. In terms of climate change, operations contribute 89%, development 6%, exploration 3%, and post-mining 2%. Additionally, for carcinogenic human toxicity, aquatic eutrophication, and depletion of metal resources, operations contribute 100% to these categories, while the other phases contribute 0%. Operations also contribute 30% to land use compared to 66% for development, 4% for exploration, and 0% for post-mining. In the case of water usage, operations contribute 75%, whereas development contributes 23%, exploration 2%, and post-mining 0%.

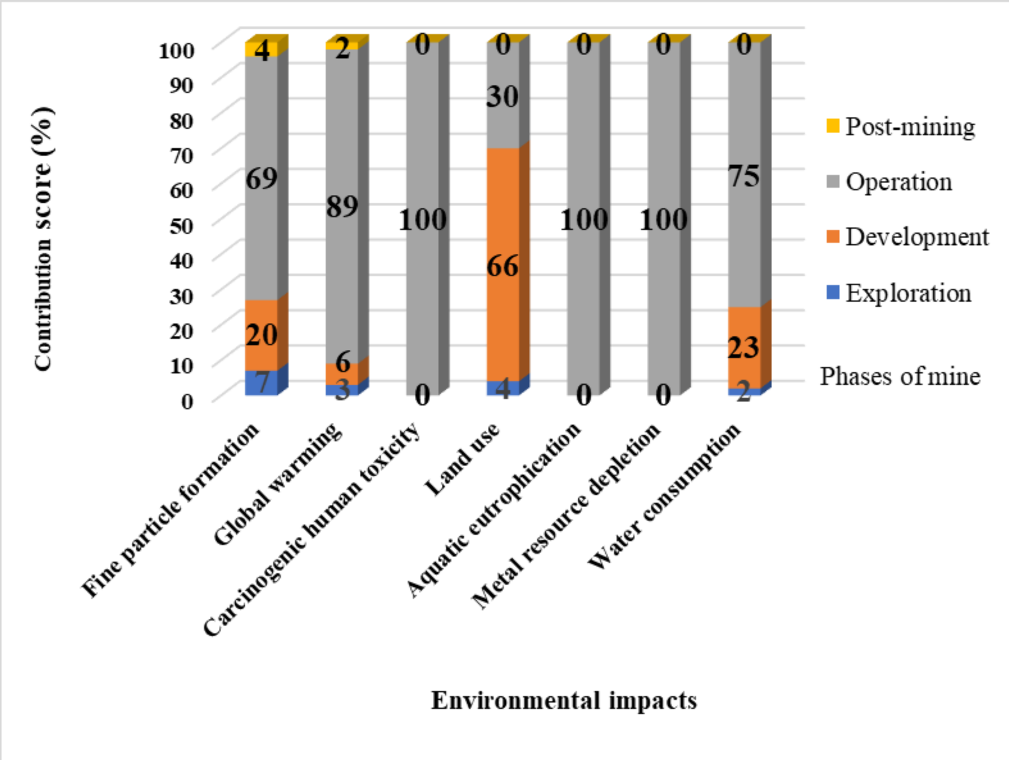

Fig. 2. All phases of mining contribution to impact category determination

3.2 ANALYSIS OF KEY SUBSTANCES CONTRIBUTIONS

Figure 3 illustrates the main substances responsible for intermediate impacts, including 66% of sulfur dioxide, 23% of nitrogen dioxide and 11% of particulate matter from diesel combustion during mining operations. Global warming is caused by 90% of the carbon dioxide, 9% of the methane and 1% of the nitrogen from diesel combustion in transport and power generation. As for the mercury released during gold processing and mining, it contributes 100% to human health. The 76% nitrogen, 15% ammonium, 6% nitrate and 3% ammoniac discharged into water contribute to aquatic eutrophication generated by the use of ammonium nitrate in gold ore extraction. Gold ore mined at 100% contributes to the depletion of metal resources. Water consumption at 75% contributes to water use.

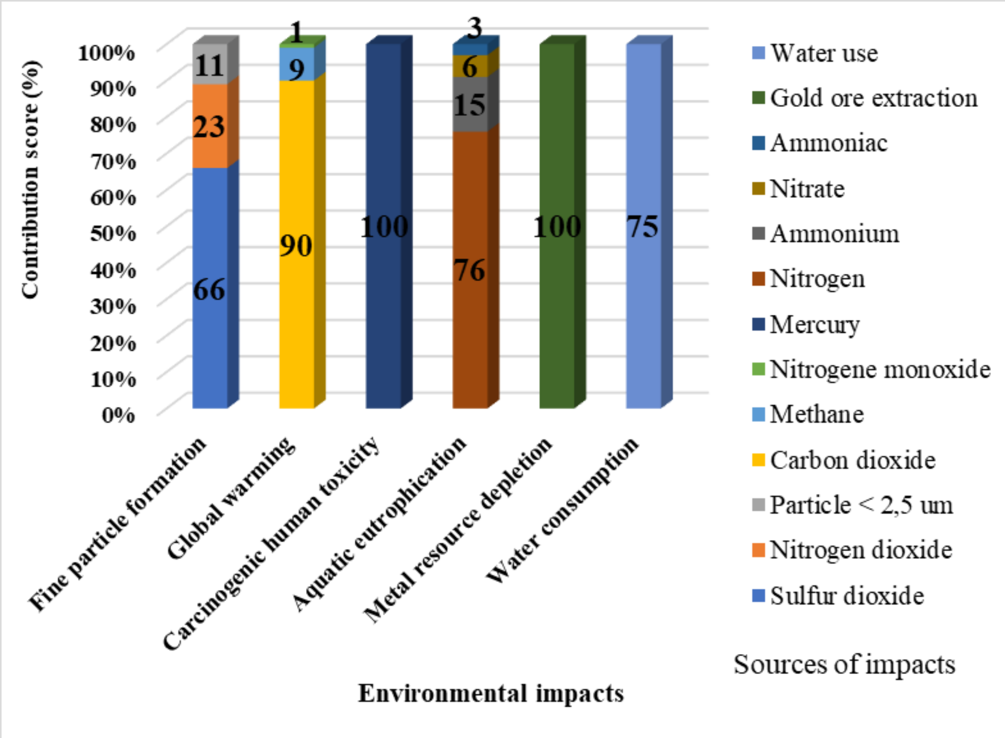

Fig. 3. key substances contribution to determined intermediate impact categories

3.3 Sensibility Analysis

Figure 4 shows the results of sensitivity analysis, comparing the IMPACT 2002+ and CML-IA methods with the ReCiPe results. The comparison focuses on climate change, carcinogenic human toxicity and aquatic eutrophication, each of which has significant values. The results show that the operating phase has a significant impact on Global warming, with respective values of 89% according to ReCiPe, 86% according to IMPACT 2002+ and 86% according to CML-IA. carcinogenic human toxicity at 100% according to ReCiPe, 96% according to IMPACT 2002+ and 94% according to CML-IA.

For aquatic eutrophication, according to ReCiPe 100%, IMPACT 2002+ 97% and CML-IA 96%. The results vary slightly due to the impact characterization model used for each method and the substances taken into account. The ReCiPe 2016 midpoint H method covers 18 impact categories, while IMPACT 2002+ and CML-IA cover 15 and 11 respectively. However, these variations do not affect the reliability of the ReCiPe 2016 method.

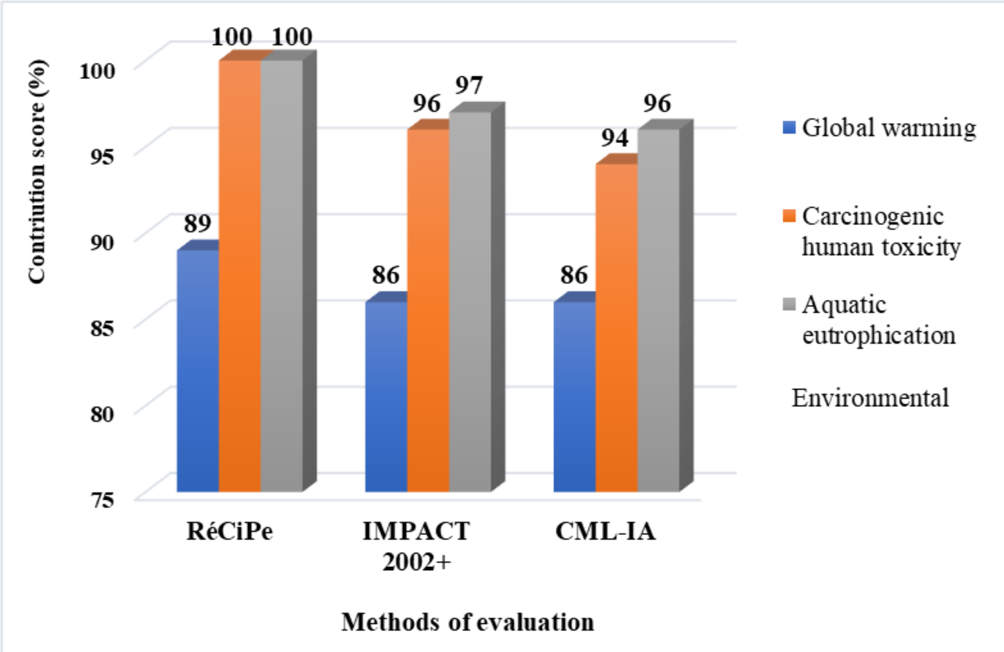

Fig. 4. ReCiPe 2016 H, IMPACT 2002+, and CML-IA Methods comparison

3.4 Global Warming

Emissions of carbon dioxide, methane and nitrous oxide are the main contributors to global warming. According to ReCiPe, carbon dioxide contributes 90%, methane 9% and nitrous oxide 1%. IMPACT 2002+ puts carbon dioxide at 91%, methane at 7% and nitrous oxide at 2%. As for CML-IA, carbon dioxide 89%, methane 6% and nitric oxide 5% (Figure 5).

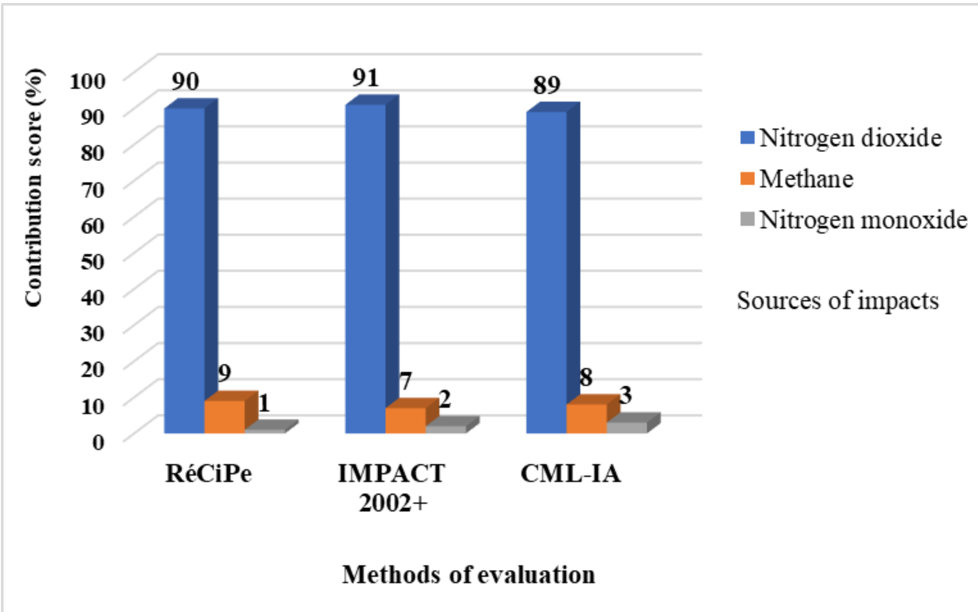

Fig. 5. Contribution of key substances to Global warming across three methods (ReCiPe, IMPACT 2002+, CML-IA)

3.5 CARCINOGENIC HUMAN TOXICITY

Mercury emissions to surface waters remain the main contributor to carcinogenic human toxicity according to the three ReCiPe, IMPACT 2002+ and CML-IA methods. With respective contributions of 100%, 70% and 50% (Figure 6). The presence of mercury in the Tabako and Farabalan rivers is linked to its use by gold miners (Figure 7 a and b).

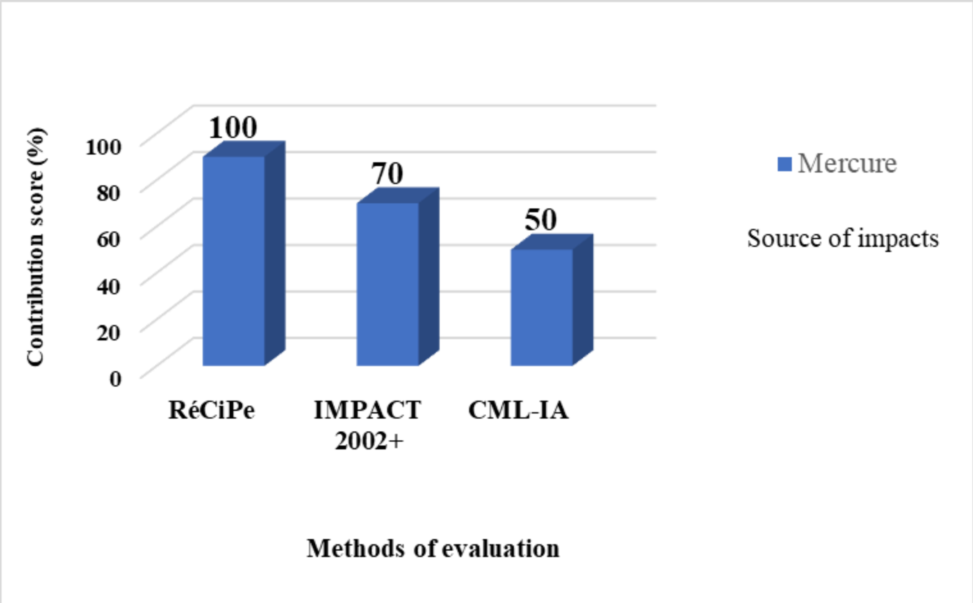

Fig. 6. Key Substances contribution to Carcinogenic human toxicity carcinogenic human toxicity across three methods (ReCiPe, IMPACT 2002+, CML-IA)

Fig. 7. a- Crushing plant 4 m upstream from Tabako; b- Washing plant in the Farabalan bed upstream

3.6 AQUATIC EUTROPHICATION

The main cause of aquatic eutrophication is the discharge of nitrogen, ammonium, nitrate, ammonia and nitrogen dioxide into water. According to ReCiPe, nitrogen is the main contributor, followed by ammonium, nitrate and ammoniac, with contributions of 76%, 15%, 6% and 3% respectively. According to IMPACT 2002+, nitrogen dioxide is the main contributor, followed by nitrogen, nitrate and ammonium, with respective contributions of 87%, 8%, 3% and 2%. As for CML-IA, nitrogen dioxide remains the main contributor, followed by nitrogen and ammonium, with contributions of 62%, 30% and 8% respectively (Figure 8). The use of ammonium nitrate for gold ore extraction would contaminate extraction pits, which would be drained by runoff into rivers via precipitation (Figure 9)

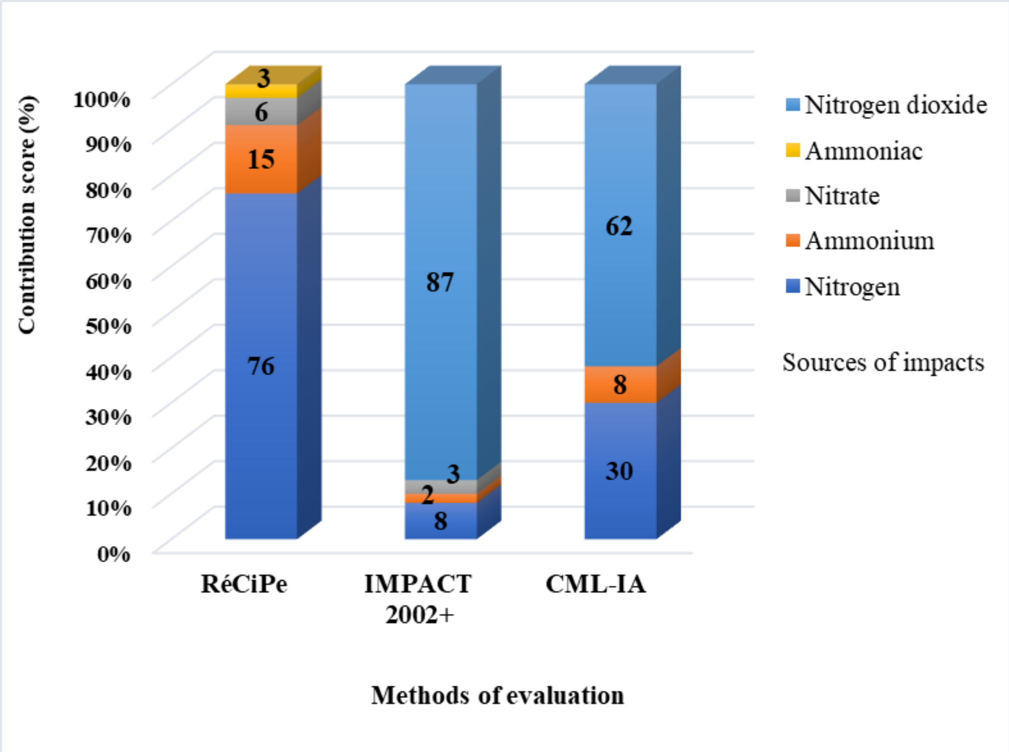

Fig. 8. Key substances contribution to Aquatic eutrophication by three methods (ReCiPe, IMPACT 2002+, CML-IA)

Fig. 9. Photo of the extraction pits (1- pit A; 2 -pit B)

3.7 Standardization Results

The results of the normalization, presented in figure 10, show that the formation of fine particles has a score equivalent to the impact of one person per year. Global warming three people per year, carcinogenic human toxicity two people per year, aquatic eutrophication two people per year. Metallic resource depletion scores two people per year, while water use scores the impact of one person per year. This shows just how much greater the impact of global warming is than that of the other impact categories. In this case, as it is a global impact, it also has the highest score. It is therefore crucial to determine an appropriate measure to mitigate the effects of this impact on the population.

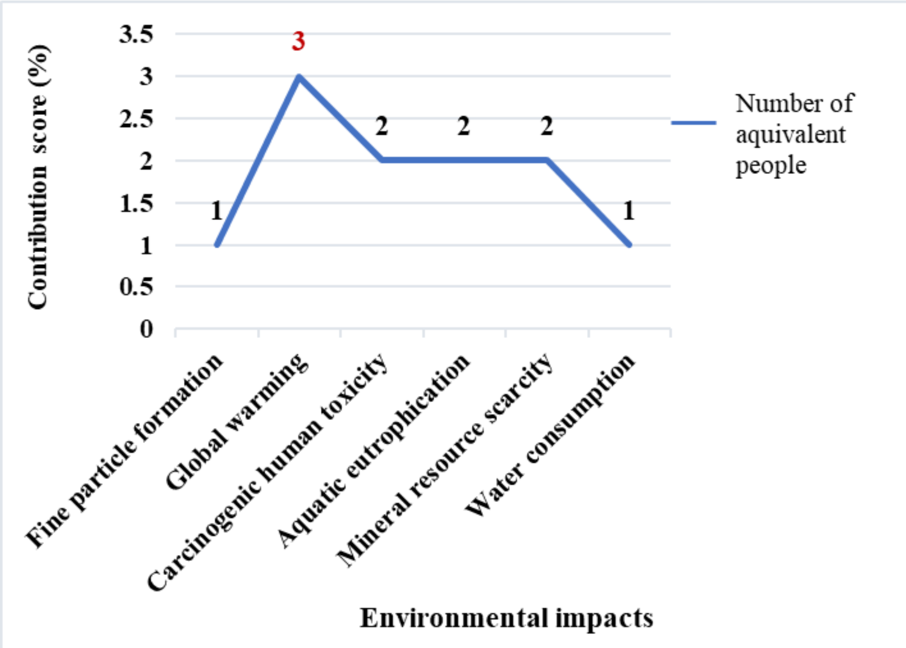

Fig. 10. Normalization Results

4 Discussion

4.1 Comparison Of Results From This Study With Previous Studies

According to the life cycle assessment (LCA) results of this study, the operational phase is the main contributor to the overall environmental impact of Semafo's gold production. This finding confirms the results of previous studies [10], [11], [12], [13], [14], which also identified the operational phase as the main contributor to overall environmental impact.

Furthermore, the impact categories identified, such as fine particle formation, climate change, non-carcinogenic human toxicity, aquatic eutrophication and metal resource depletion, align with those identified in studies by [7], [11]. Emissions of carbon dioxide, methane and nitric oxide into the air are the main contributors to climate change caused by diesel combustion in mining trucks and power generation during the ore extraction and processing process. This result is consistent with previous studies [7], [12], [15], [13], [16].

The release of mercury into water due to the use of chemicals during ore extraction and processing, as well as mining waste, are responsible for the impact on non-carcinogenic human toxicity. This result is comparable to the findings [17], [12], [13]. Gold mining is the main factor contributing to the impact of metal resource depletion, which is consistent with research [6], [12], [13].

The main factor contributing to water use is the large amount of water consumed in processing gold ore. The release of nitrogen, ammonium and nitrate into water is the main contributor to aquatic eutrophication generated by the gold mining process, a finding that corroborates that of [6]. Most LCA studies have assessed impacts at the midpoint due to low parameter uncertainty. Furthermore, the results obtained by this study are superior to those of [13].

4.2 Life Cycle Assessment (LCA) Limitations

Researchers have embarked on a series of studies on Life Cycle Assessment (LCA) in the gold mining industry to assess the environmental impacts stemming from gold production, adopting approaches ranging from cradle to gate, gate to grave, or cradle to grave. Each of these studies has demonstrated the relevance of LCA methodology within the context of the gold mining industry. Positive outcomes have been achieved, thereby guiding decisions on environmental improvement by identifying the most effective production technologies as well as strengths and weaknesses [14], [18], [19], [20].

Furthermore, only the study conducted in Côte d'Ivoire by [13] accounted for the entire life cycle, from exploration to post-mining. Each author evaluated impacts using ideal LCA methods such as ReCiPe 2016, 2013, 2009; ILCD; DEC; impact 2002+; EM-LCA; CML, etc., through various software platforms like Simapro; GaBi; GaBi combined with HSC Sim software; Arc GIS; OpenLCA, etc. However, all of these research endeavors highlighted the lack of necessary data to establish a comprehensive life cycle inventory (LCI).

The primary concern in conducting Life Cycle Assessment lies in the limited availability of data. [21] explained that LCA methodology faces three major issues: lack of data, allocation, and waste management. High-quality data required for this work are often proprietary to companies, limiting their accessibility in the public domain. The inability to adequately address site-specific impacts hampers the ability to capture the true spatial and temporal dimension of Life Cycle Impact Assessment (LCIA) results when generic data are used [20].

The limitations of LCA also explain the scarcity of free software containing comprehensive life cycle inventory (LCI) databases. Life cycle inventory datasets available in databases such as ELCD Bottles and Agribalyse, integrated into OpenLCA software, are sometimes insufficient. Many LCI datasets are available in Ecoinvent licensed databases, utilized by commercial software like Simapro and GaBi [22].

In our study, most of the data used originate from previous Environmental Impact Assessment (EIA) reports conducted in the study area before and during mine operation. Despite our efforts, gaps persist, particularly regarding construction-related data (materials, equipment, etc.), which were available in [13] work conducted in Côte d'Ivoire. Since [13] research focused on a gold mine in Côte d'Ivoire, located in West Africa, and considering the similarities among gold mines in Africa, we incorporated this data in developing a life cycle inventory tailored to our own gold mine.

5 Conclusion

The first LCA carried out in Guinea at the Kiniero gold mine (Semafo-Guinea) enabled us to identify seven categories of environmental impact, namely global warming, fine particle formation, aquatic eutrophication, non-carcinogenic human toxicity, land use, metal resource depletion and water use. The operating phase is the main contributor to the overall environmental impact of gold production at Semafo. The significant potential environmental impacts associated with this phase are: fine particle formation, global warming, non-carcinogenic human toxicity, aquatic eutrophication, depletion of metal resources and water use. The use of fossil fuels (diesel) in transport and power generation is the main source of global warming. The main pollutants emitted into the environment are carbon dioxide, sulfur dioxide, nitrogen dioxide, particulate matter, methane, nitrogen, ammonium, nitrate and mercury. Replacing diesel fuel with renewable energy such as biodiesel in transport trucks. Wind power, photovoltaic solar energy and biomass for electricity generation could reduce or limit greenhouse gas emissions.

Competing Interests

Authors have no conflicts of interest

Authors' Contributions

In the course of this study, BK developed the research protocol, collected information in the field, analyzed the data and drafted the manuscript. The manuscript was refined and translated by AO. KFJK and KRD contributed to data collection. WEN took the lead on this task and gave recommendations for carrying out the various activities and perfecting the manuscript until it was validated.

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