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Research Article

Scaling Bioleaching from Lab to Industry: A Life Cycle Assessment of Cathode Copper Production

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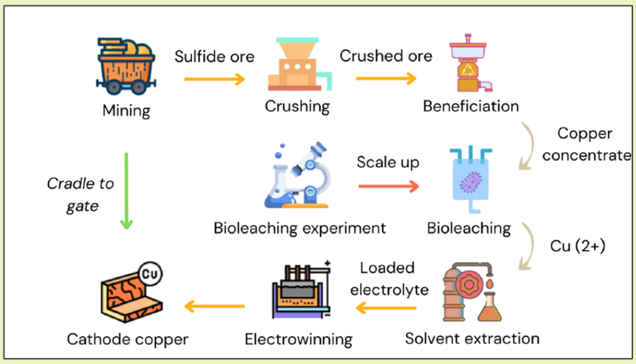
ABSTRACT: The copper industry is under growing pressure to reduce its environmental footprint and address declining ore grades, as global demand rises in parallel with the energy transition. In response, bioleaching has emerged as a promising low-carbon alternative for extracting copper from low-grade sulfide ores. This study presents the first cradle-to-gate life cycle assessment (LCA) of cathode copper production via bioleaching using laboratory-scale data scaled to an industrial context. Results show that bioleaching achieves lower greenhouse gas (GHG) emissions (6.94 kg CO_2-eq/kg copper) compared to conventional pyrometallurgy (8.45 kg CO_2-eq/kg), with a notable reduction in acidification (85%). Hotspot analysis identifies electricity, steel ball production, diesel consumption, and waste treatment as key contributors to environmental burdens. Moreover, sensitivity analysis reveals that inadequate recovery of $AgNO_3$ (50% recycling rate) could significantly elevate ozone depletion (213%), smog (191%), and fossil fuel depletion (187%). Scenario analysis indicates that integrating solar electricity could reduce GHG emissions by up to 52%. Future improvements in flotation reagent formulation, low-carbon steel production, and advanced waste treatment are recommended to further optimize the environmental performance of bioleaching.



KEYWORDS: *life cycle assessment, bioleaching, primary copper production, process scale-up*

INTRODUCTION

Copper production and supply are crucial for clean energy technologies, as highlighted by the International Energy Agency (IEA).[1] However, the copper extraction and refining process is often associated with substantial greenhouse gas (GHG) emissions, along with other pollutants. According to the International Copper Association (ICA)[2] the average carbon footprint of producing one ton of refined copper has reached 4.6 tons of CO_2. The total GHG emissions from the copper industry are projected to grow from 97.1 million tons (2018) to 102.3 million tons (2050) in the no action scenario. Furthermore, if copper demand doubles due to the expansion of clean energy technologies, GHG emissions from copper production are estimated to represent nearly 2.7% of global emissions by 2050, compared to the current 0.3%.[3]

The decarbonization of copper production has been listed as ICA's primary goal. Currently, pyrometallurgy is the major production route, accounting for approximately 80% of the total copper production.[4] However, it is involved in high temperatures and a series of high-polluting processes.[5] As the copper ore grade continues to decrease in the future, the energy usage of pyrometallurgy will grow.[6] Moreover, pyrometallurgy emits massive tailings as well. With a typical recovery rate of pyrometallurgy (87.5%), a total of 2.2 tons of slag will be produced for one ton of copper production.[7] Tailings management is the major contributor to toxicity according to the Ecoinvent database.[8] Therefore, researchers are actively exploring alternative methods for copper production. Among these methods, hydrometallurgy based on acid leaching has emerged as a pivotal approach.

As shown in Figure 1, hydrometallurgy was developed to avoid intensive energy use. The oxide ore undergoes heap leaching and SX-EW (Solvent extraction and electrowinning) processes. Heap leaching could replace the original grind-flotation circuit. Its advantages include requiring less processing and lower temperature conditions. However, its performance decreases when using it for sulfide ore (Chalcopyrite: $CuFeS_2$), this is because the 1:1 ratio of iron to copper could result in slow leaching kinetics, which also leads to excessive acid consumption.[9] Another disadvantage of hydrometallurgy is the limited availability of oxide ores, which account for less than 20% of the global copper reserves.[10] Therefore, researchers are trying to develop other leaching agents for Chalcopyrite. Bioleaching

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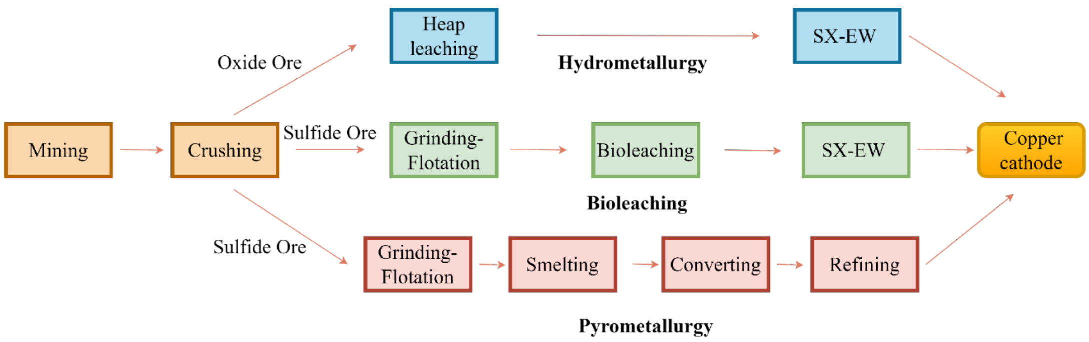

Figure 1. Comparison of three primary copper production routes (hydrometallurgy, bioleaching, and pyrometallurgy).

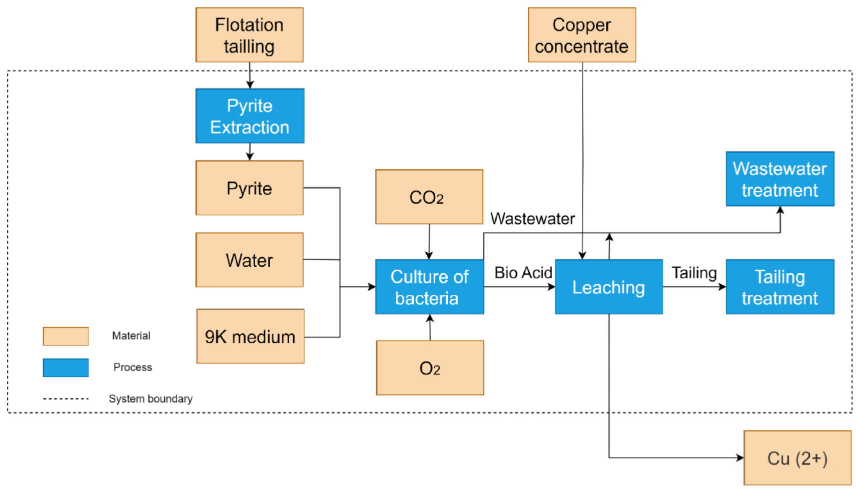

Figure 2. System boundary of bioleaching.

becomes one option because microorganisms could facilitate the oxidation of sulfide compounds into sulfates or elemental sulfur through their metabolic activities.[11] Moreover, the problem with acid leaching lies in maintaining a precise stoichiometric ratio between the acid and Cu^{2+} ions to ensure the effectiveness of the leaching process. The inherent nature of hydrometallurgy results in significant acid consumption.[12] In bioleaching, however, certain cultivation media could produce abundant acid to leach copper.[13] Several previous studies focused on heap bioleaching[14,15] a process in which bioacid reacts with copper ore that has undergone primary crushing. While this method is considered more environmentally friendly compared to pyrometallurgical and hydrometallurgical approaches, its primary limitation lies in the prolonged leaching duration, which can extend up to 10 days or even longer.[14] In this context, we developed a bioleaching process that utilizes copper concentrate as the input material (as illustrated in Figure 2), with the dual objective of minimizing environmental impact and reducing reaction time. It is worth noting that bioleaching is still in the early stages of technological development, and our experiments provide lab data to support further advancements and LCA.

Previous life cycle assessment (LCA) studies on copper production have primarily focused on conventional pyrometallurgical and hydrometallurgical routes, with limited attention to bioleaching. Recent work on heap leaching of oxidized ores has clarified several hotspots. Yang et al.[16] compared heap versus heap-agitation leaching (CML method) and reported increases of approximately 52% in cumulative energy demand and 54% in GWP for the heap-agitation route, as the heap leaching route avoids the additional energy required for grinding and agitation operations. Rabbani et al.,[17] in their LCA of heap leaching based copper production, found that electricity use, particularly in electrowinning, accounts for approximately 63% of total GHG emissions (1.7 of 2.75 t CO_2-eq per t Cu). They further showed that replacing grid power with wind or solar PV can reduce GHG emissions by approximately 53% and 38%, respectively. As an emerging technology, the life cycle environmental impact of copper bioleaching has not been well studied. Earlier, Ruan et al.[18] showed that bioheap leaching can substantially reduce emissions compared with flotation-flash smelting, with greenhouse gas emissions reduced by approximately 62.5% and sulfur dioxide emissions by about 84.9%. This study collected data from a real production facility in China, although detailed material and energy flows are available, there is a lack of technical specifics. While this work provided detailed material and energy flow data at the production scale, it lacked key technical descriptions necessary to fully understand process performance and scalability.

In this study, we conducted a life cycle assessment (LCA) of cathode copper production via bioleaching. First, the upstream production data for copper concentrate were derived through simulation and mass balance methods. Second, the laboratory-scale data for the bioleaching process were scaled up to obtain the corresponding material and energy flows required for LCA. Finally, data for the SX/EW process were sourced from literature. The findings enable us to elucidate the implications of the bioleaching process on the life cycle impacts of copper production.

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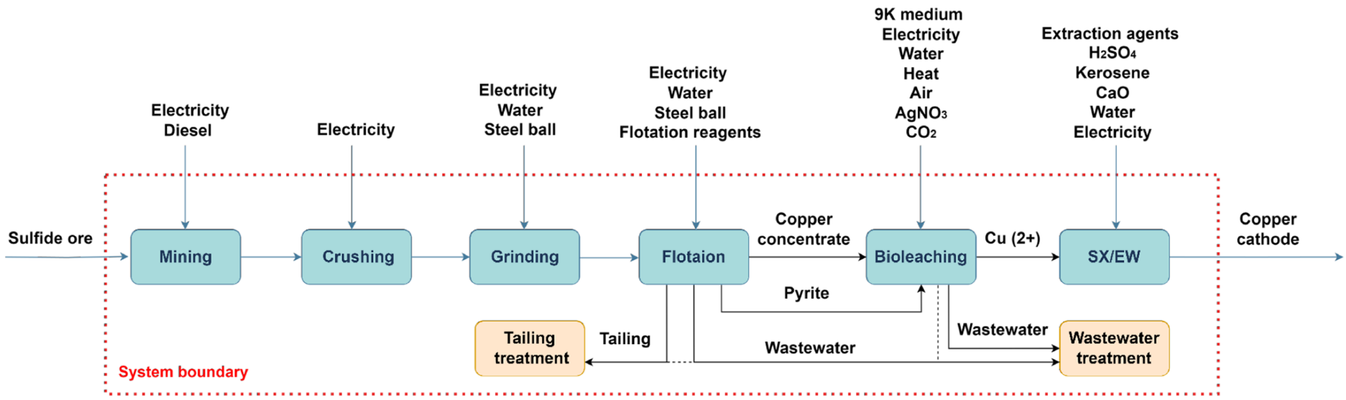

Figure 3. System boundary of cathode copper production via bioleaching.

METHODOLOGY

Upstream Production Modeling. The upstream process consists of mining, crushing, grinding, and flotation (as shown in Figure 3). The input is 0.59% sulfide ore, and the output is 22% copper concentrate. For the mining process, open-pit mining data were obtained from a report written by the U.S. Department of Energy,[19] assuming that energy consumption aligns with the "best practice scenario," given that the data were obtained in 2000. Afterward, as the crushing process only involves the electricity consumption of a crusher, we adopted a typical Bond work index of 5 kWh/ton for the primary crusher.[20] For the grinding process, METSIM was employed to simulate the system and quantify the energy consumption associated with each unit operation. Additionally, a mass balance model was developed based on detailed rougher/cleaner separation efficiency data,[20] and a typical Bond work index of 14 kWh/ton for the tower/regrind mill.[21] Furthermore, the energy consumption of the flotation cell was estimated through scale-up calculations from laboratory-scale equipment.[22] The detailed process model is provided in the [Supporting Information].

Bioleaching Experiment. Bioleaching functions by converting crushed copper ore (chalcopyrite and pyrite) into copper ions through microbial activity. It bridges the stages between the grinding-flotation circuit and SX/EW (solvent extraction and electrowinning) (as shown in Figure 2). Therefore, we used copper concentrate as the main material input, precultured microorganisms, and $AgNO_3$ as a reactant to facilitate the reaction with $CuFeS_2$. During bioleaching, electricity is required to agitate the bioreactor (48 h), and heat is required to maintain the reaction temperature. The detailed reaction can be written as follows:

$$CuFeS_2 + 4Ag^+ \rightarrow 2Ag_2S + Cu^{2+} + Fe^{2+} \tag{1}$$

$$Ag_2S + 2Fe^{3+} \rightarrow 2Ag^+ + Fe^{2+} + S \tag{2}$$

$$CuFeS_2 + 4Ag^+ \rightarrow Cu^{2+} + Fe^{2+} + 2S + 4Ag \tag{3}$$

Notably, microorganisms were cultivated before bioleaching. The microbial consortium employed in this study originated from a previously established bioreactor system characterized in detail by Free et al.[23] The dominant microbial species included *Leptospirillum ferriphilum*, together with *Acidithiobacillus* and *Sulfobacillus* spp. This consortium was maintained in 9K medium and used as the principal bioleaching inoculum. In the microorganism cultivation process, pyrite is necessary for microorganism cultivation, and it is produced from chalcopyrite tailings. Therefore, we also modeled the pyrite production process in [Supporting Information]. The microorganism cultivation process using pyrite lasts for 48 h. Moreover, this process contributes to carbon capture by facilitating microbial carbon fixation, where CO_2 serves as a carbon source for microbial growth. The University of Utah conducted both microorganism cultivation and leaching experiments under various temperature, solids concentration, and $AgNO_3$ dosage conditions. Results show an overall copper leaching efficiency of 35% to 96% under different reaction conditions (details of experiments can be found in [Supporting Information]). In line with our principle of minimizing copper loss, we chose the highest leaching efficiency scenario for further analysis. In the following section, we construct a process flow diagram for the bioleaching system and estimate industrial heat consumption to establish the corresponding mass and energy flows.

Bioleaching Process Scale-Up and Energy Model. Here, we establish the scaled-up bioleaching process based on experimental results. The mass flows were presented in Figure 2.

The main material input of the bioleaching process is the copper concentrate (the output product of the flotation process). The output of the bioleaching process is 1 kg of Cu^{2+} (dissolved metal). The bioleaching process includes two main steps-culture of bacteria and metal leaching. Pyrite (Produced from copper flotation tailing), water, 9K medium ({$(NH_4)_2SO_4$ and K_2HPO_4), CO_2, and O_2 (air is used in the experiment) were used to cultivate microorganisms. The biogenerated acid produced from this process was used to leach copper concentrate in the next step. For the leaching process, copper concentrate is the main input material with biogenerated acid and $AgNO_3$ consumption. The output includes Cu^{2+} (desired product), tailings, and wastewater (waste flow). The waste material and water generated in this process will proceed to the waste treatment process. We referred to the assessment results of tailing and wastewater treatment processes (treatment of sulfidic tailings and average treatment of wastewater) in the ecoinvent database.[8] Based on experiment results and established mass flow, the energy/mass flow data were calculated using the following equations:

$$Q_c = \frac{Q_{in}}{m_{cp} \times f_{Cu} \times \eta_{bioleaching} \times \eta_{SX/EW}} \tag{4}$$

where Q_{in} denotes the heat input, representing the experimental heat consumption (kWh), m_{cp} is the chalcopyrite input in the bioleaching process (kg), $\eta_{bioleaching}$ is the bioleaching efficiency (%), $\eta_{SX/EW}$ is the SX/EW efficiency (%), f_{Cu} is the copper

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content in chalcopyrite (36.4%) and Q_c is the heat consumption per unit copper production (kWh/kg copper).

In this study, the laboratory data were scaled up to model copper bioleaching at the industrial bioreactor scale. A 5,000 m^3 bioreactor equipped with an industrial heating system was assumed. This volume represents a representative industrial scale for bioleaching applications[24] and is consistent with the capacity that can be realized in a new plant-size production facility.[25] As industrial systems typically operate in continuous or long-duration batch modes, only the heat required to maintain the operating temperature was considered. The initial startup heat was excluded, as it becomes negligible when normalized over the annual total copper production (exceeding 200 tons). Based on the heat balance data reported by[26] for industrial-scale bioreactors, the one-time startup heating requirement is estimated to contribute less than 0.5% to the total heat demand of the overall process. For temperature maintenance, the total heat input is determined by the overall heat transfer coefficient (U), the heat exchange area (A), the temperature difference between the bioreactor contents and the heating medium (ΔT), the duration of the bioleaching process (t_{leaching}), and the thermal efficiency of the heating system (η).[27] These parameters were used in the following equation to estimate the industrial-scale heat requirement for continuous bioleaching operations. This equation, as well as the key parameters applied (U and A), have been validated against empirical data from comparable industrial fermenters and heat exchange systems.[28]

$$Q_{\text{in}} = \frac{U \cdot A \cdot \Delta T \cdot t_{\text{leaching}}}{\eta} \tag{5}$$

where U is the overall heat transfer coefficient between the bioreactor and the ambient environment ($W \cdot m^{-2} \cdot K^{-1}$), A is the heat exchange area of the bioreactor (m^2), and ΔT is the temperature difference between the operating temperature and the surrounding environment (K), t_{leaching} is the duration of the bioleaching process (h), and η is the thermal efficiency of the heating system (%).

Moreover, in the laboratory system, $AgNO_3$ was treated as a one-time additive and assumed to be fully consumed. However, in industrial practice, silver ions can often be fully recovered and reused through recirculation or selective recovery processes. In this study, the $AgNO_3$ consumption was calculated based on a hypothetical industrial-scale bioreactor with a working volume of 5,000 m^3. The concentrations of $AgNO_3$ and 9K medium were assumed to remain consistent with those used in the laboratory system. Therefore, the $AgNO_3$ consumption was calculated based on the amount added per leaching cycle using the following equations, assuming a 95% recovery rate.[29]

$$m_{AgNO_3} = \frac{c_{AgNO_3} \times V_{\text{bioreactor}} \times (1 - R_{AgNO_3})}{m_{cp} \times f_{Cu} \times \eta_{\text{bioleaching}} \times \eta_{SX/EW}} \tag{6}$$

where c_{AgNO_3} refers to the experimentally determined $AgNO_3$ consumption ($kg \cdot L^{-1}$); $V_{\text{bioreactor}}$ denotes the bioreactor volume (10,000 L), R_{AgNO_3} is the recycling rate of $AgNO_3$, and m_{AgNO_3} is the $AgNO_3$ consumption per unit copper production (kg/kg copper).

$$m_{\text{medium}} = \frac{c_{\text{medium}} \times V_{\text{bioreactor}} \times (1 - R_{\text{medium}})}{m_{cp} \times f_{Cu} \times \eta_{\text{bioleaching}} \times \eta_{SX/EW}} \tag{7}$$

where c_{medium} refers to the experimentally determined cultivation medium consumption ($kg \cdot L^{-1}$), and m_{medium} is the medium consumption per unit copper production (kg/kg copper).

$$CO_2 \text{ capture rate} = \frac{CO_2 \text{ intake rate} \times V_{\text{bioreactor}} \times t_{\text{leaching}}}{\text{Chalcopy rite input (kg)} \times f_{Cu} \times \eta_{\text{bioleaching}} \times \eta_{SX/EW}} \tag{8}$$

where CO_2 intake rate is the CO_2 intake rate during bioleaching ($mg\ L^{-1}\ min^{-1}$), and CO_2 capture rate is the CO_2 captured per unit copper (kg/kg-copper). In this study, a preliminary CO_2 intake rate of approximately 30 $mg\ L^{-1}\ h^{-1}$ was estimated from a mass balance on residual organic carbon in the solid phase, which is consistent with trends reported in a previous study.[30]

The 0.15 g/L $AgNO_3$, 70 °c, and 96% efficiency were chosen for calculation. In addition, water consumption and waste generation data could be found in [Supporting Information].

Life Cycle Assessment. The goal of this LCA study is to evaluate the environmental impacts of cathode copper production via bioleaching, using a cradle-to-gate LCA approach. The TRACI 2.1 method[8] is employed for life cycle impact assessment as both the copper concentrate production and bioleaching experiments are based in the United States. The scope of this study includes environmental impacts of sulfide ore mining, mineral processing for copper concentrate production, solubilization of copper ions Cu^{2+} via bioleaching and further SX/EW process to produce ≥ 99.99% cathode copper. The treatment of solid waste and wastewater is also included in this study. The functional unit is chosen as 1 kg of cathode copper, as 1 kg enables the results to be comparable with conventional copper production methods (pyrometallurgy and hydrometallurgy). The system boundary is shown as follows:

Figure 3 represents the input (0.59% sulfide ore), output (cathode copper), and energy/material flows of the system boundary. Main energy inputs include heat, diesel, and electricity. Waste treatment includes tailing treatment from flotation and wastewater from bioleaching. The energy and material usage data of SX/EW process were collected from.[18] Detailed energy/material information is shown in the next section (Life Cycle Inventory (LCI) data). Based on the LCI results, the overall life cycle environmental impacts are summarized in Table 2. The TRACI v2.1 method (US, 2008) was selected for impact assessment.[8] As the copper production and experiment are based in Utah, the electricity emission factor of US-WECC (United States- Western Electricity Coordinating Council) was chosen.[8] For flotation reagents, we used the impact factor of Sodium ethyl xanthate.[31] For steel ball making, as the majority of grinding media are composed of chromium alloy steel,[32] the market for steel, chromium steel 18/8, hot rolled process,[8] was selected to represent steel ball production.

RESULTS AND DISCUSSION

This section first presents the life cycle inventory (LCI) data to provide a comprehensive overview of all material/energy inputs and process emissions (section 3.1). Subsequently, the overall life cycle assessment (LCA) results are reported and compared with conventional pyrometallurgical and hydrometallurgical routes to highlight the environmental advantages of bioleaching (section 3.2). To further explore the drivers of environmental impacts, a hotspot analysis is conducted from both material/energy flow and process-level perspectives (section 3.3). Finally,

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we conduct two additional analyses to address data sensitivity identified in this study, including a sensitivity analysis on the recovery rates of $AgNO_3$ and 9K medium (section 3.4), and a scenario analysis considering potential low-carbon electricity transitions (section 3.5).

Life Cycle Inventory. This section exhibits the LCI data from simulation, experiments and literature. Table 1 shows the life cycle inventory results of copper production through bioleaching. Overall, electricity is used in all subprocesses. In the mining process, electricity accounts for approximately 33% of total energy consumption, and diesel accounts for the rest energy consumption. An average number of 0.136 kg blasting materials[8] is consumed per kg cathode copper production. In crushing-grinding-flotation process, steel balls are consumed in primary ball mill of grinding and regrind mill of flotation. Total of nearly 0.16 kg of steel balls are consumed per kg cathode copper production. Additionally, the flotation process generates a significant amount of solid waste (tailings), amounting to approximately 180 kg per kg of copper produced.

Table 1. LCI of Copper Extraction via Bioleaching (Reference Product: 1 kg of Copper)

Process	Flow	Unit	Amount
Mining	Blasting	kg	1.36×10^{-01}
	Electricity	kWh	1.13×10^{00}
	Diesel	kWh	2.98×10^{00}
Crushing	Electricity	kWh	1.02×10^{00}
Grinding	Electricity	kWh	3.22×10^{00}
	Steel ball	ton	1.60×10^{-04}
Flotation	Electricity	kWh	2.35×10^{00}
	Water	ton	8.39×10^{-02}
	Steel ball	ton	6.29×10^{-06}
	Flotation reagents	kg	1.89×10^{-01}
Concentrate tailing treatment	Tailing treatment	ton	1.80×10^{-01}
	$(NH_4)_2SO_4$	kg	3.15×10^{-02}
	K_2HPO_4	kg	5.24×10^{-03}
	$AgNO_3$	kg	3.15×10^{-03}
Bioleaching	Electricity	kWh	6.54×10^{-01}
	Water	ton	1.05×10^{-03}
	Heat	kWh	3.66×10^{-01}
CO_2intake	CO_2	kg	6.10×10^{-01}
Bioleaching wastewater	Wastewater treatment	ton	1.05×10^{-06}
Bioleaching tailing	Tailing treatment	ton	1.83×10^{-02}
SX/EW	Extraction agents	kg	6.19×10^{-03}
	H_2SO_4	kg	2.45×10^{-01}
	Kerosene (used as diluent)	kg	4.38×10^{-02}
	Water	ton	1.24×10^{-02}
	$CaCO_3$	ton	1.02×10^{-03}
	Electricity	kWh	2.51×10^{00}

The bioleaching stage exhibits the highest water demand among all subprocesses. Moreover, the CO_2 captured reaches 0.61 kg/kg copper in bioleaching. The captured CO_2 was calculated using a constant CO_2 intake rate in bioreactor (30 mg/L/h, 5,000 m^3, 48 h, see [Supporting Information]). Notably, electricity consumption in the solvent extraction and electrowinning (SX/EW) stage exceeds 2.5 kWh/kg, closely trailing that of grinding (3.2 kWh/kg), which is conventionally regarded as the most energy-intensive step in upstream copper concentrate production.

Overall Life Cycle Environmental Impacts. The overall life cycle environmental impacts are shown in Table 2.

Table 2. Life Cycle Assessment Results of Bioleaching of 1 kg of Copper Compared to Global Copper Production (TRACI V2.1)[a]

Environmental Impact Indicators	Bioleaching	Copper, cathode {GLO}, market[8]	Copper cathode {GLO}, electrorefining[8]
Ozone depletion (kg CFC-11 equiv)	1.07×10^{-7}	8.48×10^{-8}	1.05×10^{-7}
Global warming (kg CO_2 eq)	6.94	6.91	8.45
Smog (kg O_3 eq)	1.85	1.59	1.69
Acidification (kg SO_2 eq)	8.98×10^{-2}	4.32×10^{-1}	5.90×10^{-1}
Eutrophication (kg N eq)	3.83×10^{-1}	3.32×10^{-1}	2.89×10^{-1}
Carcinogenics (CTUh)	1.46×10^{-5}	1.25×10^{-5}	1.55×10^{-5}
Noncarcinogenics (CTUh)	3.75×10^{-4}	1.26×10^{-4}	1.51×10^{-4}
Respiratory effects (kg $PM_{2.5}$ eq)	1.90×10^{-2}	4.38×10^{-2}	6.20×10^{-2}
Ecotoxicity (CTUe)	1.06×10^{4}	1.16×10^{4}	9.77×10^{3}
Fossil fuel depletion (MJ)	10.6	6.32	7.71

[a]"Copper, cathode {GLO}, market" refers to *Copper, cathode {GLO} | market for copper, cathode | Cut-off, S* (ecoinvent v3.10), and "Copper, cathode {GLO}, electrorefining" refers to *Copper, cathode {GLO} | electrorefining of copper, anode | Cut-off, S* (ecoinvent v3.10). All comparisons with ecoinvent data sets are harmonized for functional unit (1 kg copper cathode), system boundary (cradle-to-gate), system model (ecoinvent v3.10, Cutoff, S), and impact method (TRACI v2.1).

Compared to a previous study that assessed the LCA of copper production via pyrometallurgy from 0.71% copper ore grade,[33] which reported greenhouse gas (GHG) emissions of 6 kg CO_2-eq per kg copper, our study shows higher emissions of 6.94 kg CO_2-eq/kg copper. This discrepancy is primarily due to the exclusion of material inputs such as steel ball consumption, flotation reagents, and solvent extraction reagents ,[33] which contribute significantly to the embodied energy and emissions. For instance, in pyrometallurgical copper production (Copper cathode GLO, electrorefining,[8] the steel ball production process accounts for nearly 10% of total GHG emissions. Nevertheless, when the results are normalized to the same amount of ore processed, our bioleaching system (40.9 kg CO_2-eq/kg ore at 0.59% Cu grade and 83.5% recovery) achieves a lower footprint than pyrometallurgy reported in the previous study[33] (42.6 kg CO_2-eq/kg ore at 0.71% Cu grade and 81.9% recovery).

Our results are further compared to conventional copper production processes, as shown in Table 2. The global copper production data set ("Copper, cathode {GLO}" from ecoinvent) includes a market mix of hydrometallurgical processes (solvent extraction and electrowinning) and pyrometallurgical processes (electrorefining of copper anodes).[8] To ensure transparent comparability across sources, we standardized the functional unit (1 kg cathode at gate), boundary (cradle-to-gate), impact method (TRACI v2.1), and database family (ecoinvent v3.10, Cutoff, S). Compared to the global average GHG emissions (6.91 kg CO_2-eq/kg copper), the bioleaching route assessed in this study shows comparable GHG emissions (6.94 kg CO_2-eq/kg copper). However, in terms of

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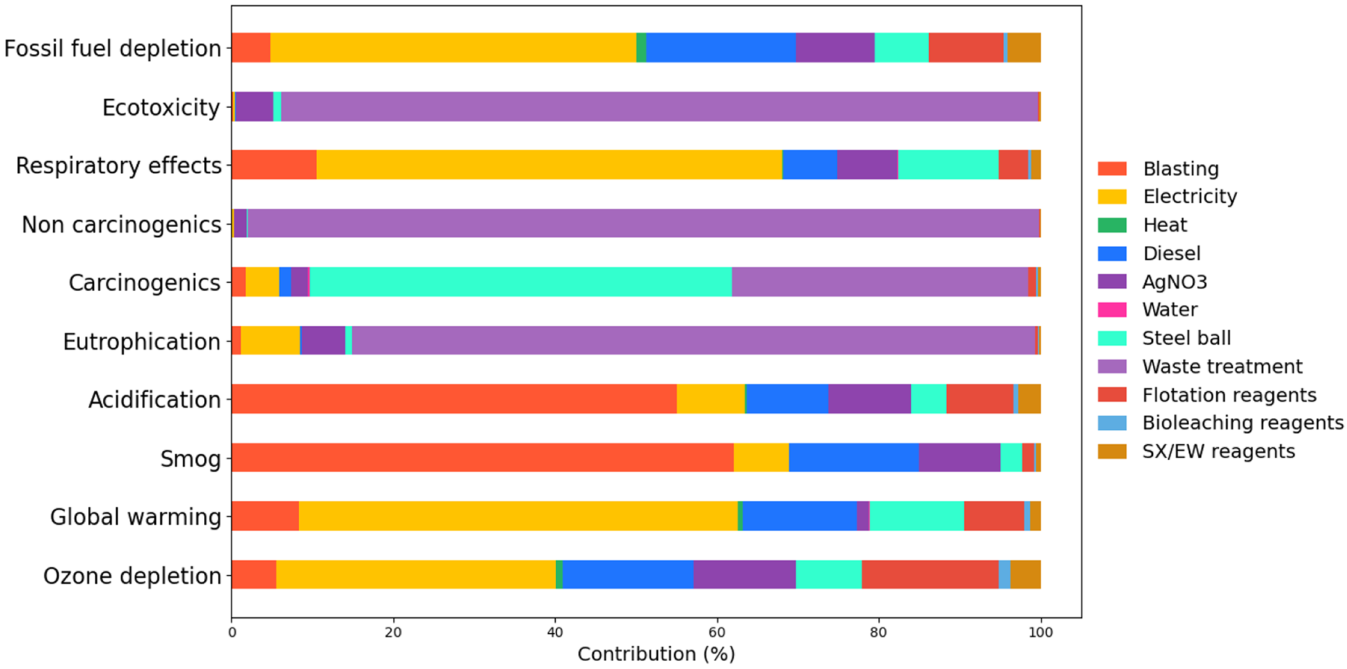
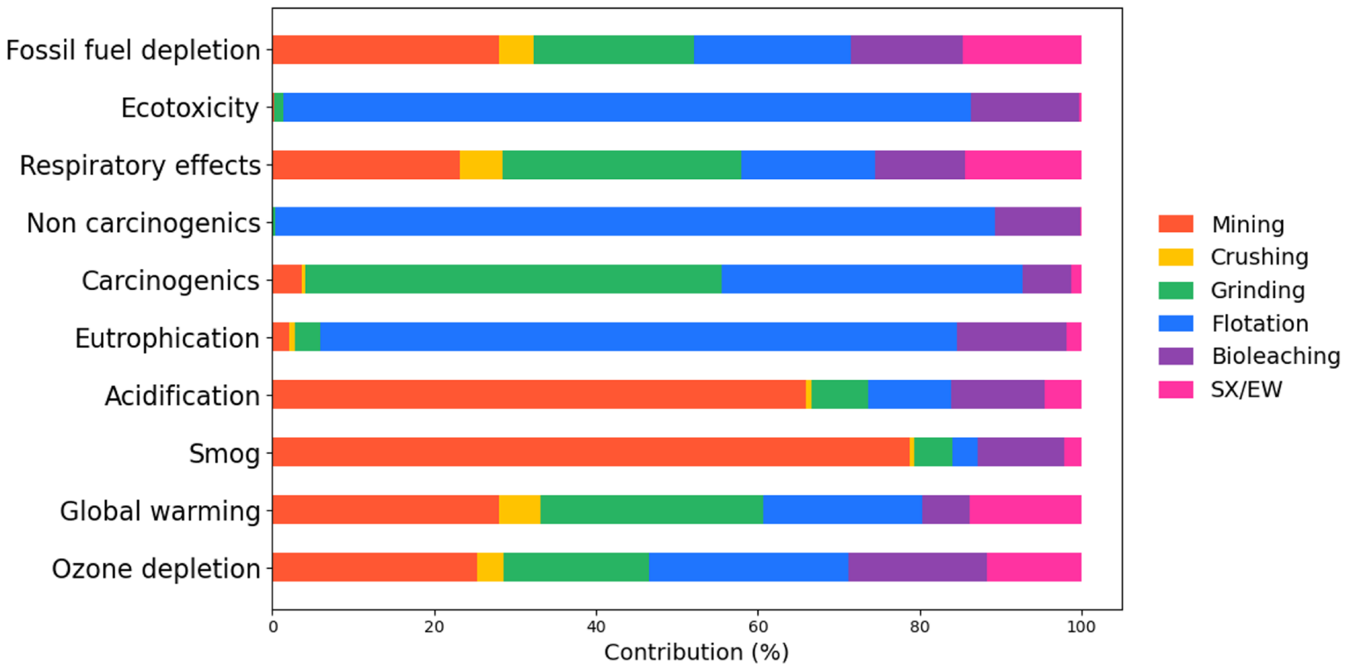


(a) Contributions by material and energy inputs



(b) Contributions by process stage

Figure 4. Contribution analysis of life cycle impacts for copper production via bioleaching.

acidification, smog, noncarcinogenic effects, and fossil fuel depletion, global copper production performs better than bioleaching. This can be attributed to the use of hydropower (5 kWh/kg copper) in the hydrometallurgical route.

When compared specifically to pyrometallurgical copper production, bioleaching exhibits notably lower GHG emissions (8.45 vs 6.94 kg CO_2-eq/kg copper). However, pyrometallurgy still shows lower impacts in terms of noncarcinogenics and fossil fuel depletion. This difference may stem from the limited diesel usage reported for pyrometallurgical processes-only 0.01 MJ of diesel per kg copper according to ecoinvent.[8] In contrast, diesel consumption in our upstream mining stage reaches 2.98 kWh/kg copper. This is substantially higher than the 0.01 MJ/kg reported in ecoinvent, likely due to differences in system boundaries. Specifically, our study includes diesel consumption for drilling, blasting, hauling, and other mobile equipment across

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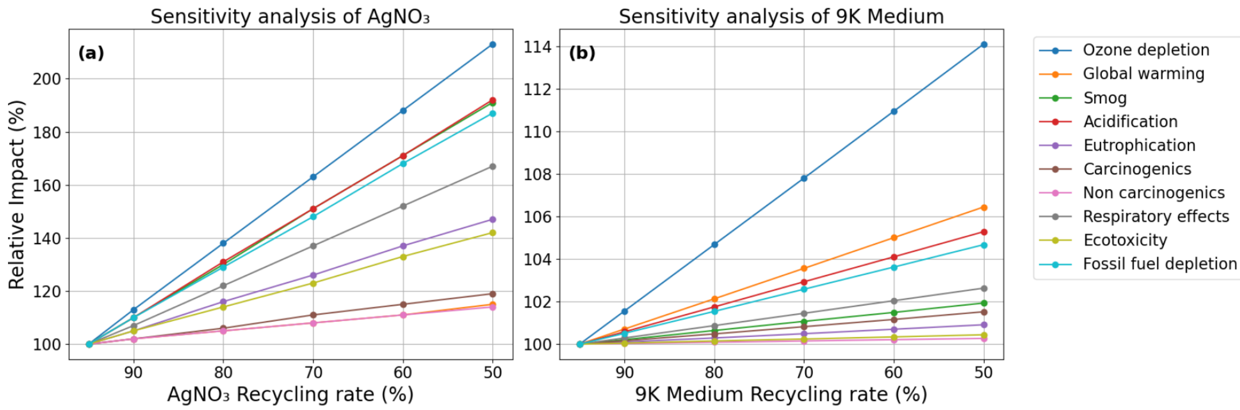

Figure 5. Sensitivity analysis of life cycle impacts with respect to recycling rates of (a) $AgNO_3$ and (b) 9K medium.

the entire upstream mining operation, whereas the ecoinvent data set might only account for diesel used in ore transport. Such boundary differences can substantially influence fossil fuel depletion and noncarcinogenic impact results, potentially leading to underestimation of these impacts in data sets with narrower boundaries. These inconsistencies can also reduce the clarity of comparative LCAs, as observed differences may reflect methodological choices such as variations in inventory scope rather than the inherent advantages or disadvantages of a given production pathway. Overall, bioleaching achieves a significant reduction in global warming potential (18%) and acidification impacts (85%) compared to pyrometallurgical production, while maintaining comparable performance across other environmental categories.

Contribution Analysis. A detailed analysis of the material and energy contributions is presented in Figure 4a. Electricity, steel ball, waste treatment, and diesel are identified as environmental hotspots. Electricity consumption is the dominant contributor across multiple environmental impact categories, particularly fossil fuel depletion, global warming, and ozone depletion. The steel ball, due to its energy-intensive hot-rolling process, accounts for approximately 12% of global warming and 15% of respiratory effects. Waste treatment makes a substantial contribution to ecotoxicity and noncarcinogenic impacts, predominantly arising from the disposal of flotation tailings. These impacts are primarily driven by the leaching of heavy metals, notably copper, zinc, lead, cadmium, and nickel. Diesel emerges as a major contributor to smog formation and acidification, and is also the second-largest contributor to fossil fuel depletion.

Figure 4b exhibits the process-level contribution results. Flotation is the dominant driver of ecotoxicity due to tailing treatment process. Flotation is identified as the major contributor to eutrophication and the second-largest contributor to ozone depletion, likely due to the use of flotation reagents. The mining process significantly contributes to smog formation, which can be linked to the use of explosives during blasting. Notably, grinding shows considerable contributions across nearly all environmental categories, suggesting the critical environmental impacts associated with electricity and steel ball consumption in this stage. Overall, approximately 60% of the environmental impacts are concentrated in the upstream processes of bioleaching, including mining, crushing, grinding, and flotation.

Sensitivity Analysis. In industrial practice, the recycling rates of $AgNO_3$ and 9K medium are typically uncertain. Therefore, a sensitivity analysis was conducted over a range of 95% to 50%. According to Lindblom et al.,[34] approximately 89−95% of silver can be recovered from Ag-containing solutions. As shown in Figure 5, $AgNO_3$ exhibits a significant influence on environmental impacts, with relative increases ranging from 114% to 213%. The most pronounced impact is observed in ozone depletion (213%), followed by smog formation (191%), and fossil fuel depletion (187%). These elevated values could be attributed to the pyrometallurgical recovery of silver from copper anode slimes. This process often involves diesel combustion, contributing to fossil fuel depletion and NO_x emissions, thereby increasing smog formation. Furthermore, the high-temperature nature of the process requires extensive usage of halogenated refrigerants for cooling, which significantly contributes to ozone depletion. However, the impact on global warming is relatively moderate (110%), since the GHG emissions associated with silver recovery from copper anode slimes are relatively low (less than 50 kg CO_2-eq per kg Ag.[8] In comparison, the environmental impacts associated with the 9K medium are considerably lower, with increases limited to the range of 0.27% to 13.8%. This is primarily due to the relatively low environmental burdens associated with the production of $(NH_4)_2SO_4$ and K_2HPO_4. As indicated in the contribution analysis, these commonly used compounds present lower environmental impacts than $AgNO_3$ and flotation reagents.

In addition to reagent recycling, we also examined the sensitivity of environmental impacts to leaching efficiency (as shown in the leaching efficiency sheet in the Supporting Information). Lower efficiencies substantially and nonlinearly amplify environmental burdens across all categories. In some cases, the impacts increase by more than an order of magnitude, mainly because of the intensified upstream energy and material requirements at lower yields. This confirms that the highest experimental efficiency, used in our base case, represents a meaningful best-case or upper-bound benchmark for the environmental performance of bioleaching.

Electricity Decarbonization Scenario. Since electricity is the leading contributor to the overall environmental burden and current technologies offer limited potential for reducing electricity consumption, the use of clean electricity has become a prominent strategy in decarbonization efforts. Given that the copper mine in Utah has already begun purchasing solar power,[35] alternative scenarios incorporating solar electricity were evaluated (30−100% = x% solar electricity). The solar electricity scenario is modeled using the "Electricity, high voltage RoW | electricity production, solar tower power plant, 20

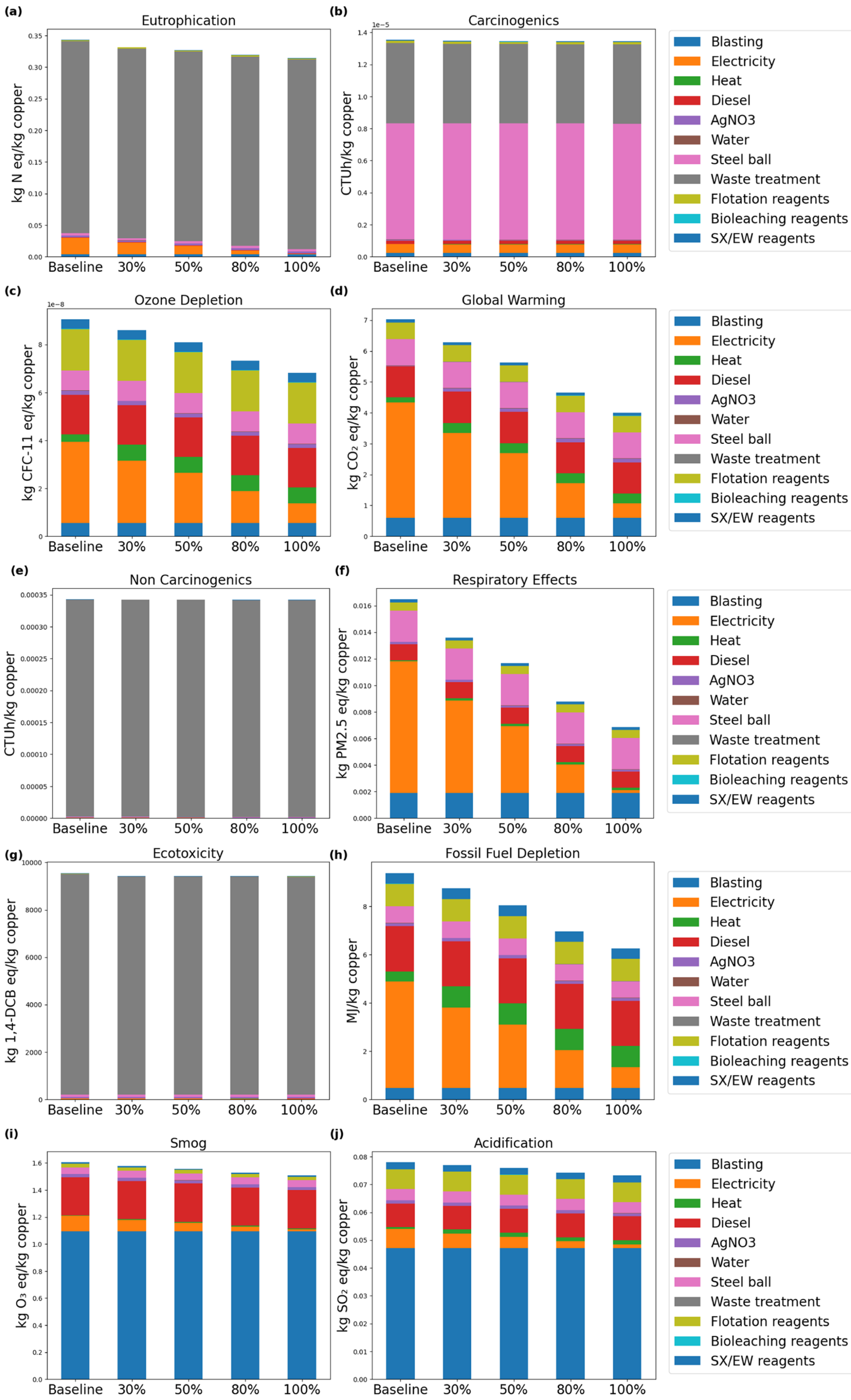

Figure 6. Electricity decarbonization scenario: (a) eutrophication, (b) carcinogenics, (c) ozone depletion, (d) global warming, (e) non-carcinogenics, (f) respiratory effects, (g) ecotoxicity, (h) fossil fuel depletion, (i) smog, (j) acidification.

MW | Cut-off, S" from the ecoinvent data set,[8] which includes a 440 MWh molten-salt thermal storage system with inherent storage and balancing capability.

As shown in Figure 6, using 100% solar electricity could lead to a reduction of 0.15% to 51.7% across various environmental impact categories. The most notable reductions are observed in

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climate change (51.7%) and respiratory effects (55.8%). Even when only 30% of the current Utah grid electricity is replaced with solar power, the global warming potential decreases to below 6 kg CO_2-eq per kg of copper. Furthermore, when more than 80% of electricity is substituted with solar energy, steel ball production and diesel become the dominant contributors to the global warming impact, accounting for approximately half of the total. A similar shift is observed for respiratory effects, with steel balls and diesel collectively responsible for a comparable share of the impact in 50% of solar electricity scenario. This could be attributed to the release of airborne pollutants such as NO_x, SO_2, and fine particulate matter ($PM_{2.5}$) during diesel combustion[36] and the hot rolling process of steel balls.[37]

In addition to climate change and respiratory effects, considerable reductions are observed in ozone and fossil fuel depletion. With 100% solar electricity, the two categories could be reduced approximately 26.2% and 36.5% respectively. For ozone depletion, flotation reagents and diesel become the dominant contributors in 100% solar electricity scenario. This is primarily due to the presence of ozone-depleting substances, such as chlorofluorocarbons,[38] in the upstream production of flotation reagents. Diesel, on the other hand, contributes ozone depletion through emissions of halogenated compounds associated with the petroleum extraction process.[39]

In terms of Eutrophication, Non-Carcinogenics, Ecotoxicity, Carcinogenics, Smog and acidification, solar electricity shows minor impacts on these environmental indicators. For Eutrophication, Non-Carcinogenics, Ecotoxicity, waste treatment is the dominant contributor, accounting for over 90%. For smog and acidification, blasting is the major contributor, accounting for more than 60% of smog and more than 50% of acidification. This is due to the significant amounts of NO_x and SO_2 released from blasting process.[40] For carcinogenics, steel balls account for approximately 50%. This is primarily attributed to the heavy metals (e.g., Pb, Cd, Cr) and highly toxic persistent organic pollutants such as polychlorinated dibenzo-*p*-dioxins and furans (PCDD/Fs) emitted in upstream steel manufacturing processes (sintering and blast furnace operations).[41]

LIMITATIONS

This study has several limitations. First, the LCI for wastewater treatment relies on ecoinvent's generic "wastewater, average" profile because process-specific inventories for bioleaching effluents containing Cu_2S particulates or dissolved silver are not available; toxicity-related impacts may therefore be underestimated. Second, when extrapolating laboratory findings to industrial operation, the dominant sources of uncertainty arise from both ore grade variability and laboratory-to-industry efficiency gaps. In practice, copper ore grade can vary widely (0.1−0.6% Cu); lower grades necessitate processing more ore to produce the same mass of copper, which increases energy demand, material handling, and tailings generation in upstream unit operations such as mining, crushing, and beneficiation. Moreover, laboratory efficiencies (35−96%) may not be fully reproducible at industrial scale due to heat and mass transfer limitations, potentially altering reagent consumption and energy requirements. Third, the analysis does not fully capture indirect trade-offs and potential side effects. For example, the adoption of solar electricity could introduce land use burdens for photovoltaic installations, while additional reagents required to enhance silver recovery carry embodied environmental impacts from their production and supply chains.

FUTURE RECOMMENDATIONS

Although electricity decarbonization has shown significant potential in reducing global warming potential, fossil fuel depletion, and respiratory effects (Section 3.5), its influence on other environmental indicators such as eutrophication, ecotoxicity, noncarcinogenics, and carcinogenics remains limited. Therefore, to enhance the overall environmental competitiveness of copper production via bioleaching compared to conventional technologies (Section 3.2), several additional strategies are recommended.

First, the development and adoption of alternative or next-generation flotation reagents should be prioritized to mitigate ozone depletion impacts. This may involve screening low-impact chemical substitutes or employing green chemistry approaches in reagent synthesis.[42] Second, decarbonization of steel ball manufacturing should be pursued because this supply chain is a significant contributor to carcinogenics and respiratory effects. Hydrogen-based direct reduction[43] and electric arc furnaces[44] supplied by low carbon electricity can substantially reduce cradle-to-gate steel emissions. In addition, adopting high-efficiency, geometry-optimized grinding media with improved wear performance can lower media consumption and further decrease upstream impacts.[45] Third, future LCA studies should evaluate the integration of advanced tailings management, specifically filtered tailings (dry stacking),[46] to mitigate long-term environmental liabilities and exposure pathways linked to eutrophication, noncarcinogenic toxicity, and ecotoxicity. Finally, future work should integrate techno-economic analysis (TEA) with LCA to capture the trade-offs between environmental and economic performance. Since leaching efficiency exerts a disproportionate influence on upstream energy and material requirements, incorporating efficiency-dependent cost models would provide a more comprehensive assessment of industrial scalability.

CONCLUSION

In conclusion, this paper conducted the first LCA study on bioleaching of primary cathode copper production using laboratory data. A detailed, scaled up energy/material consumption model was developed to represent bioleaching process. The results demonstrate that, compared to pyrometallurgical routes, bioleaching offers superior environmental performance across most impact categories. Furthermore, the analysis identified electricity consumption, steel ball production, diesel usage, and waste treatment as key environmental hotspots. To address the uncertainties inherent in early stage laboratory data, the study further incorporated sensitivity and low-carbon scenario analyses focused on electricity use. Quantitatively, the cradle-to-gate greenhouse gas (GHG) emissions associated with producing 1 kg of cathode copper via bioleaching were estimated to be 6.94 kg CO_2-eq. Under the 100% solar electricity scenario, the most significant reductions were observed in climate change (52%) and respiratory effects (58%). Notable benefits were also observed in ozone depletion and fossil fuel depletion, with reductions of approximately 30% and 40%, respectively. To further improve the environmental performance of bioleaching, this study recommended future development strategies for flotation reagents, steel ball manufacturing and waste treatment technologies.

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■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.5c06793.

Experimental protocols, scale-up assumptions, foreground LCA inventory, TRACI impact factors, mining energy, electricity-mix scenarios, sensitivity analysis (XLSX)

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Notes

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