Environmental impact of mining and beneficiation of copper sulphate mine based on life cycle assessment

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Abstract
China is a major producer of copper concentrate as its smelting capacity continues to expand dramatically. The present study analyzes the life cycle environmental impact of copper concentrate production, along with selection of a typical copper sulphate mine in China. Life cycle assessment (LCA) was conducted using SimaPro with ReCiPe 2016 method. The midpoint and endpoint results were performed with uncertainty information based on Monte Carlo calculation. Normalization of midpoint results revealed that impact from the marine ecotoxicity category was the largest contributor to the total environmental impact, followed by freshwater ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, and terrestrial ecotoxicity. The mining activity, backfilling activity, and electricity generation were proved to be the dominant factors. In addition, main processes and substances to the identified key categories were also classified. Specifically, the cement production in the backfilling process, blasting activity, on-site emission, and electricity generation was regarded as the critical processes. Copper to air and zinc emission to water were considered the critical substances. The sensitivity analysis revealed the most effective measure to solve the environmental problems caused by the concentrate production process, which is controlling on-site emissions and reducing pollution from cement production. Finally, the corresponding technical and management measures were proposed to facilitate the development of cleaner metal industry.

Keywords Life cycle assessment · Copper concentration production · On-site emission · Tailing pollution · Backfill materials

Introduction
Copper is popularly used in the manufacture of electronic equipment, wiring, alloys as well as building materials (Beylot and Villeneuve 2015), paving the way for modern civilization. Mining, beneficiation, and metallurgy are the three indispensable stages in the copper production process. Raw ore, concentrate, and metallic copper are the products of each stage, respectively. Due to the convenience of transportation and storage, copper concentrate occupies an important position in the world copper market. China is a major producer and consumer of copper concentrates. In the period 2001–2017, China’s copper concentrate production increased by about one million tons, accounting for approximately 19% of the total global copper concentrate growth (CSY 2018; He 2018). The production of copper concentrate has contributed tremendously to China’s rapid development, but it also brought a series of environmental pollution problems. The dust and toxic gases generated during the blasting process induce severely adverse effects on mining personnel and the surrounding ecosystem. The mining and beneficiation process consumes a lot of energy and power (Hong et al. 2018), and produces crushed stones made of unwanted minerals, and a mixture of processing fluids from mining and beneficiation processes (Beylot and Villeneuvre 2017), thus contributing to severe environment problems, especially for marine fauna and flora (Gu et al. 2012; Farjana et al. 2019a; Sun et al. 2019). In addition, improper treatments of tailings may lead to severely heavy metal pollution problems (Jahed Armaghani et al. 2016). In rural areas of China, mining activities have proven to be
one of the most serious sources of soil heavy metal pollution (Dong et al. 2011; Yang et al. 2018). Therefore, systematically assessing the environmental impact of the copper concentrate production process is essential to reduce energy consumption and alleviate environmental pollution, as well as provide practical suggestions on the shortage of copper resources and sustainable development.

Life cycle assessment has become intensively applied in mineral processing industries by quantifying the impacts of all inputs and outputs within the production process (Asif and Chen 2016; Guinée et al. 2011; Norgate et al. 2007). In the last 15 years, remarkable research has been published involving aluminum (Farjana et al. 2019a, b, c; Tan and Khoo 2005), iron (Ferreira and Leite 2015; Gan and Griffin 2018), gold (Farjana et al. 2019c; Norgate and Haque 2012), lead (Yang et al. 2019), zinc (Qi et al. 2017), coal (Wang et al. 2016; Tao et al. 2021), etc. Copper has also attracted increasing attention all over the world, and a number of researches have focused on the environmental pollution caused by the production process based on the life cycle assessment method. The environmental impacts of the refined and reclaimed copper were analyzed based on LCA. These studies covered the environmental impacts of the energy consumption, carbon intensity, tailing treatment, different smelting technologies and equipment selection on copper manufacture, which have propelled clean production in the copper industry (Chen et al. 2019; Rubin et al. 2014; Song et al. 2017; Moreau et al. 2021; Adrianto et al. 2022; Yang et al. 2022). However, due to the limitations of the times and the development of disciplines, these investigations have been unable to well reflect the problems existing in current copper production. For example, in many studies, only special impact category results were identified, other serious hot spot pollution issues were ignored (Memary et al. 2012; Norgate et al. 2007; Northey et al. 2013). In addition, there were few studies on the copper mines in China for the lack of relevant data (Ekman Nilsson et al. 2017; Haque and Norgate 2014). Chen et al. compared the environmental impact of the China’s refined and reclaimed copper production, but there was a lack of complete uncertainty information in the study and the uncertainty data obtained were relatively large, leading to deviations in the research findings (Hong et al. 2019). In a majority of the past studies, only refined metals were considered, ignoring that a production process combining mining and beneficiation process with concentrates as their final products, so it is typical to explore the environmental impact of the concentrate production process. Upon drilling and blasting, the copper sulfide ore was broken underground, and then sent to the site of the mineral processing industry through lifting and transportation system for further crushing and grinding. The grinding products were transported to the next stage for flotation, copper concentrate and copper tailings were received through the copper flotation process initially, and subsequently, the by-products high-sulfur and low-sulfur concentrates were obtained from the graded copper tailings.

The grade of copper in this mine was 0.883% and that of the sulfur was 8.447%. The mine also contained a few other metals of gold 0.140 g/t and silver 10.658 g/t. However, owing to the low grade of gold and silver, the complex extraction process accompanied with the high cost; they were not exported as products. After a series of mining and dressing processes, three products were finally obtained as follows: copper concentrate, high-sulfur concentrate, and low-sulfur concentrate as by-products.

Materials and methods

Background introduction

The data source of this study was from the project feasibility assessment plan of a typical copper sulfide mine in Jiangxi Province, China. Like most mining enterprises in China, this mine adopts a combination of mining and beneficiation process with concentrates as their final products, while the sulfur concentrate is always produced as well in the beneficiation process of copper concentrate production because of the interests of mining companies. Therefore, it is highly required to perform overall environmental impact analysis of copper concentrates and by-product sulfur concentrates.

To address the foregoing problems, this study assessed the environmental impacts of concentrate production based on copper sulphate mines in China. First, the ore mining and beneficiation process were analyzed through LCA method with the economic allocation of all co-products. Second, midpoint results of 18 environmental impact categories and endpoint results of 3 impact categories were examined with uncertainty information. Moreover, the entire concentrate production process was divided into four groups and 10 sub-processes, and then, main processes and substances to the key impact categories were classified in contribution analysis. Eventually, sensitivity analysis was conducted to provide more effective and practical policy insights for effective decision making in the copper sulphate mine production, and even the entire metallurgical industry.
LCA of copper sulfide ore mining and beneficiation

Functional unit and system boundary

Functional unit can provide a quantified reference for related inputs and outputs of an investigated system (ISO 2006), which should be identified first in life cycle assessment. In this study, the mining process of one tonne of copper-sulfur raw ore was selected as the functional unit. One tonne raw ore would be approximately transformed into 0.03 tonne of copper concentrate, 0.14 tonne of high-sulfur concentrate, and 0.02 tonne of low-sulfur concentrate through the mining and beneficiation process. Economic and quality distributions are the two most chosen distribution methods. Although the production volume of sulfur concentrate is large, its economic value is much low compared to copper concentrate. More importantly, copper concentrate is regarded as the main product for output, so that the choice of economic distribution in this paper is more reasonable, since it can better express the relative significance of products. Therefore, economic allocation was applied in our study to analyze the environmental pollution of the production process of the copper concentrate and its by-product sulfur concentrates.

The calculation results are given in Table 1. While mining one tonne of copper-sulfur ore, the copper concentrate obtained accounted for 95.78% of the environmental allocation, the high-sulfur and the low-sulfur concentrate obtained accounted for 3.79% and 0.43%, respectively.

System boundaries were established by applying a cradle-to-gate approach as shown in Fig. 1. The end-of-life product stages or environmental emissions for the concentration ore were not included. Raw materials and energy consumption, road transportation, direct emissions, and waste disposal were considered for each process. The raw materials were transported from the urban area eight kilometers away from the mining area. Due to the short distance between the mining and beneficiation sites, internal transportation mainly considered the distance of 1.5 km from the mining area to the waste rock dump.

After a series of mining and dressing processes, copper (23% grade), low-sulfur (grade 35%), and high-sulfur (grade 45%) concentrates were finally obtained. The one tonne raw ore of the mining enterprise could produce 0.03 tonne copper concentrate, 0.14 tonne high sulfur concentrate, 0.02 tonne low sulfur concentrate, and 0.845 tonne tailings (about 24% of the tailings go to the waste rock dump, 56% of the tailings were mixed with cement for backfilling, and the remaining 20% entered the tailings pond) after processes. Additionally, the ore loss rate in the mining and beneficiation process was around 6–8%.

LCIA methodology

SimaPro is one of the leading software programs utilized for life cycle assessment studies worldwide, providing easy access and integrity with renowned and validated databases like EcoInvent, USGS, and AusLCI, containing numerous datasets of mining and mineral processing industries (Kliphers 1997), and the newest available software version was employed in this study. A life cycle impact assessment (LCIA) was conducted at both midpoint and endpoint level by employing the ReCiPe 2016 method (updated and extended version of ReCiPe 2008), which is one of the most commonly used indicator approaches in the LCA analysis (Goedkoop et al. 2009; Schryver et al. 2009). The characterization factors used were representative of the global scale, instead of the European scale as it was done in ReCiPe 2008. ReCiPe 2016 consists of both midpoint (problem oriented) and endpoint (damage oriented) impact categories, available for three different perspectives: individualist (I), hierarchist (H), and egalitarian (E). Midpoint categories include global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health), fine particulate matter formation, ozone formation (terrestrial ecosystems), terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, and water consumption. Endpoint categories include human health, ecosystems, and resources. Figure 2 shows the relations between the midpoint impact category and the endpoint area of production (Huijbregts et al. 2020). The dotted line means there is no constant mid-to-endpoint factor

| Table 1 | Economic allocation of concentrates |
|---------|-----------------------------------|
| Product | Yield (t) | Unite price (USD) | Yield proportion | Total price (USD) | Economic allocation (environmental allocation) |
| Copper concentrate | 8.87E4 | 4598.05 | 16.71% | 4.08E8 | 95.78% |
| High sulfur concentrate | 3.82E5 | 42.24 | 71.96% | 1.61E8 | 3.79% |
| Low sulfur concentrate | 6.01E4 | 30.17 | 11.33% | 1.81E6 | 0.43% |
Fig. 1 System boundary for LCA analysis

Fig. 2 The relations between the midpoint impact category and the endpoint area of production
for fossil resources. Normalization was conducted to analyze the share of different impact categories to the overall environmental impact and achieve comparable midpoint results (Hong et al. 2018). More details on ReCiPe 2016 method are available on the website of the Institute of Environmental Science in Leiden University of the Netherlands (IESLUN 2018). Uncertainty analysis was conducted based on Monte-Carlo calculation, using 1000 runs simulation.

**Life cycle inventory and data sources**

All data input and output were within the function unit of the mining and beneficiation process of one tonne copper sulfide ore. The foreground data, mainly including the consumption of raw materials and energy in each process, external and internal transportation, on-site emissions, and waste disposal, were collected from a typical copper sulfide mine in China. The background data as the production of generic materials, energy, transport, and waste management were obtained by the Ecoinvent 3.5 databases, one of the most advanced life cycle inventory database covering the basic data of China and other countries (Duce et al. 2016; Ecoinvent Centre 2015). It should be pointed that for the lack of China-related information, data based on global national production conditions or western country production conditions were selected. In addition, the uncertainty analysis of the data was required; lognormal distribution was always assumed in Ecoinvent to present the measurements. The typical feature of the lognormal distribution is that the square of the geometric standard deviation covers a 95% confidence interval. For example, if the square of the set standard deviation is 1.2, it means that about 95% of the measured values are distributed between the mean value divided by 1.2 and the mean value multiplied by 1.2. Ecoinvent uses the pedigree matrix to estimate the geometric standard deviation, which was developed by Weidema. In recent years, Ecoinvent 3 pedigree matrix has updated to the most advanced version that is most suitable for the current situation (Bo 1998; Frischknecht et al. 2005; Tao et al. 2019). Each data presented was evaluated based on five criteria and basic uncertainty factor (depending on the type of data). The formula can be expressed in the following form.

\[
GSD^2 = \exp \left[ \frac{\ln(U_1)^2 + \ln(U_2)^2 + \ln(U_3)^2 + \ln(U_4)^2 + \ln(U_5)^2 + \ln(U_6)^2}{2} \right]
\]

The factors \( U_1 \)–\( U_5 \) refer to the scores in the reliability, completeness, temporal correlation, geographical correlation, and further technology, respectively. The factor \( Ub \) refers to the basic uncertainty factor. Table 2 presents the life cycle inventory and the calculation results of uncertainty data.

**Results and discussion**

**LCIA midpoint results**

Table 3 shows the LCIA midpoint results for one tonne copper concentrate production, calculated by ReCiPe 2016 method. The mining and beneficiation process of one tonne copper sulfide ore is listed as a basic functional unit. 0.03 tonnes copper concentrate, 0.14 tonnes high-sulfur concentrate, and 0.02 tonnes low-sulfur concentrate obtained from one tonne raw ore were performed based on the economic allocation principle. Uncertainty analysis results were presented as geometric square deviation (GSD\(^2\)) for each impact category. The confidence interval of GSD\(^2\) was set at 95%, which means 95% of the uncertain results obtained by 1000 Monte Carlo Simulation were within the range of dividing and multiplying the midpoint result value by GSD\(^2\) (Tao et al. 2019). For the global warming category of copper concentrate, the midpoint value was 3407.31 kg CO\(_2\) eq and the GSD\(^2\) value was 1.10, so the 95% confidence interval ranged between 3097.55 and 3748.04 CO\(_2\) eq.

In addition, in order to solve the incompatibility of units and compare the results, the normalization of midpoint results was performed. The normalization indicates to what extent an impact category indicator result has a relatively high or a relatively low value as compared to a reference. It can be seen from Fig. 3 that the impact on marine ecotoxicity contributed the largest to the overall environmental impact; the freshwater ecotoxicity, human toxicity (both carcinogenic and non-carcinogenic), and terrestrial ecotoxicity also exhibited significant contributions, while the environmental impacts from other categories were negligible.

**LCIA endpoint results**

Table 4 illustrates the LCIA endpoint results. Uncertainty information was presented GSD\(^2\) for each of the three impact categories. For example, in terms of copper concentrate, the potential impact on human health was 6.95E-03 DALY (disability-adjusted life years) and the corresponding GSD\(^2\) was 1.08. Such findings revealed that impact on human health category varied between 6.44E-03 DALY to
7.51E-03 DALY, with a 95% confidence interval. In addition, the dominant contributors of the three endpoint impact categories are defined in Table 4. Electricity generation, cement consumption, and blasting were the main causes to human health and ecosystems, while for resource category, copper ore mining took almost half of the environmental responsibility, accounting for 41.4%; cement consumption and electricity generation contributed 29.5% and 15.5%, respectively.

### Dominant contributor analysis

#### Contributions of main groups

To analyze and compare the environmental impact of different groups for copper concentrate production, the mining and beneficiation of copper sulfide ore process is divided into the following four groups: extraction process, copper and sulfur flotation process, tailing treatment, and auxiliary

| Inventory                  | Substance         | Amount | Unit | GSD² |
|----------------------------|-------------------|--------|------|------|
| Element in ore             | Copper            | 8.83   | kg   | 1.16 |
|                            | Sulfur            | 84.47  | kg   | 1.16 |
|                            | Gold              | 0.14   | g    | 1.16 |
|                            | Silver            | 10.66  | g    | 1.16 |
| Raw material and energy consumption | Explosive         | 0.89   | kg   | 1.16 |
|                            | Land occupation   | 13.00×10⁴ | m²  | 1.58 |
|                            | Water             | 4.04   | t    | 1.19 |
|                            | Electricity       | 67.35  | kwh  | 1.20 |
|                            | Diesel            | 0.29   | kg   | 1.24 |
|                            | Cleft timber       | 0.17   | kg   | 1.24 |
|                            | Lime              | 7.50   | kg   | 1.24 |
|                            | Alloy             | 1.57   | g    | 1.24 |
|                            | Steel             | 0.19   | kg   | 1.24 |
|                            | Cement            | 0.07   | t    | 1.16 |
|                            | Sand              | 0.08   | t    | 1.16 |
|                            | Sodium hydroxide  | 51.94  | g    | 2.10 |
|                            | Carbon disulfide  | 98.69  | g    | 2.10 |
|                            | Ethanol           | 59.45  | g    | 2.10 |
|                            | Terpenic oil      | 68     | g    | 2.10 |
| Emission to air            | Carbon dioxide    | 0.51   | kg   | 2.15 |
|                            | Carbon monoxide   | 43.39  | g    | 5.94 |
|                            | Nitrogen oxides   | 344.94 | g    | 2.37 |
|                            | Sulfur dioxide    | 662.40 | mg   | 2.10 |
|                            | Particulates, < 10 um | 1980   | mg   | 2.77 |
| Emission to water          | COD               | 4.05   | mg   | 1.58 |
|                            | BOD               | 1.35   | mg   | 1.58 |
|                            | Suspended solid (SS) | 48.82 | g    | 1.58 |
|                            | Copper            | 964.40 | mg   | 5.07 |
|                            | Lead              | 668    | mg   | 5.07 |
|                            | Zinc              | 964.20 | mg   | 5.07 |
|                            | Arsenic           | 213.76 | mg   | 5.07 |
|                            | Cadmium           | 167.50 | mg   | 1.58 |
|                            | Chromium          | 13.36  | mg   | 5.07 |
|                            | Ammonia nitrogen  | 540    | mg   | 1.58 |
| Emission to soil           | Tailings          | 845    | kg   | 1.16 |
|                            | Hazardous waste   | 0.13   | kg   | 1.53 |
| Transportation             | Lorry (freight, 16–32 metric ton) | 12.50 | tkm  | 2.06 |
| Products                   | Copper concentrates | 0.03 | t    | 1.16 |
|                            | High-sulfur concentrate | 0.14 | t    | 1.16 |
|                            | Low-sulfur concentrate | 0.02 | t    | 1.16 |
The auxiliary systems include ventilation, compression, drainage, road transportation, and consumption of living areas. Figure 4 presents the analysis results, and the extraction process accounts for more than half of the shares in stratospheric ozone depletion, ozone formation (human health), ozone formation (terrestrial ecosystems), and mineral resource scarcity, especially for stratospheric ozone depletion (80%) and mineral resource scarcity (96%). The flotation process was the main cause of fine particulate matter formation, freshwater eutrophication, marine eutrophication, human carcinogenic toxicity, land use, and fossil resource scarcity. Tailing treatment had the greatest impact on ionizing radiation and terrestrial ecotoxicity. The auxiliary system was responsible for 74% of the water consumption due to the provision of domestic water. For terrestrial acidification, the extraction and flotation processes were the main contributions, while for global warming, flotation process and tailing treatment were the main contributions, accounting for 41% and 45%, respectively. In addition, for the freshwater ecotoxicity and marine ecotoxicity as well as human non-carcinogenic toxicity, the excavation process,

| Category                               | Amount     | Unit          | Dominant contributors                                      | GSD² |
|----------------------------------------|------------|---------------|------------------------------------------------------------|------|
| Human health                           | 6.95E-03   | DALY           | Electricity (40.2%) + cement (37%) + blasting (16.7%)       | 1.08 |
| Ecosystems                             | 1.61E-05   | species.yr    | Cement (39.6%) + electricity (35.2%) + blasting (18.3%)    | 1.08 |
| Resources                              | 172.62     | USD2013       | Ore mining (41.4%) + cement (29.5%) + electricity (15.5%)  | 1.08 |

**Table 3** LCIA midpoint results

**Table 4** LCIA endpoint results for one tonne copper concentrate production

**Fig. 3** Normalized LCIA midpoint results for one tonne copper concentrate production
flotation process, and tailing treatment, each takes about one-third of the environmental burden.

Contributions of main sub-processes

In order to obtain clearer environmental impact analysis results and guide the cleaner production of copper sulfide mines, the foregoing four groups were further subdivided into 10 processes: mining, backfilling, milling, tailing dam, chemical consumption, electricity, transportation, living consumption, and others. Figure 5 indicates that all impact categories could be mainly attributed to the mining activity, backfilling activity, and electricity generation, except for water consumption and ionizing radiation. Electricity and backfilling activity dominantly affected the role in global warming, human carcinogenic toxicity, fossil resource scarcity, freshwater eutrophication, and marine eutrophication. Meanwhile, mining activity was the main cause for ozone formation (both human health and terrestrial ecosystems). In particular, mining activity took more than 80% of the environmental burden for stratospheric ozone depletion and mineral resource scarcity. Although tailing dam, chemical consumption, and milling activity did not account for a large proportion of environmental impacts, they influenced all 18 environmental impact categories, which were most evident in terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, and human non-carcinogenic toxicity. Additionally, chemical consumption and backfilling were the significant reasons for ionizing radiation. Land use was mainly caused by mining activity, backfilling activity, chemical consumption, and electricity, and water use in living areas was the most dominant contributor to water consumption.

Process contributor to the key categories

As shown by the normalized LCIA midpoint results in Fig. 3, the marine ecotoxicity, freshwater ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, and terrestrial ecotoxicity were the prominent categories of the overall environmental impacts. In addition, global warming had been taken into account as a hot environmental issue in recent years. Thus, the above six environmental impact categories were defined as key environmental impact categories. To evaluate the process roles on these key categories, process contribution analysis was performed within the system boundary, the results were presented in Fig. 6. It was found that the cement production, electricity generation, blasting pollution, transportation, on-site emissions, and steel production were the main process contributors to these key categories.
and cement production, electricity generation, and blasting pollution contribute to all six key categories. Cement production was the main reason for global warming, terrestrial ecotoxicity, and human non-carcinogenic toxicity, accounting for 53.56%, 37.68%, and 28.90%, respectively. While for human carcinogenic toxicity, marine ecotoxicity, and freshwater ecotoxicity, electricity generation played a significant role, accounting for 52.41%, 30.56%, and 30.42%, respectively. In addition, on-site emissions, mainly from mining dust, wastewater discharge during mining and beneficiation process, and heavy metal pollution in tailings, had a greater impact on the marine ecotoxicity, freshwater ecotoxicity, and human non-carcinogenic toxicity. It should be noted that steel production, mainly from the consumption of steel balls in the dressing and grinding process, exhibited a certain impact on human carcinogenic toxicity, accounting for 11.79%.

**Substance contributor to key categories**

To further clarify the specific pollutants, Fig. 7 illustrates the contributions of major substances to the key categories. The dominant contributors to climate change were carbon dioxide, which is mainly released from coal-burning electricity generation and diesel combustion to air. Copper to air and zinc to air contribute 68.6% and 9.9% to the terrestrial ecotoxicity respectively, and others like nickel to air, vanadium to air, and mercury to air demonstrated a minor impact. The contribution of chromium emission to water is the highest for human carcinogenic toxicity, while for human non-carcinogenic toxicity, zinc emission to water was the most significant factor, accounting for 87.7%. For the impact of freshwater ecotoxicity and marine ecotoxicity, the main contributor was zinc emission, followed by copper emission to water, vanadium emission to water, and chromium to water. In summary, the substances above were identified as specific pollutants that should be strictly controlled by improving the energy efficiency and reducing on-site emissions during ore mining and beneficiation process of copper sulfide mine.

**Sensitivity analysis**

To examine the most effective method of reducing the environmental pollution in copper concentrate production, sensitivity analysis of main process contributors on the identified key categories was conducted. The variation coefficient of the input value of the dominant process was all set at 5%, the assumptions were changed, and then, the LCA was recalculated. Table 5 presents the analysis results. Tailing pollution
had the highest variation in the global warming, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, and human non-carcinogenic toxicity. Particularly, the cement production in tailing treatment plays a key role. For example, a 5% reduction in tailing pollution will result in an environmental benefit of 2.82% in the global warming category while a 5% reduction in cement consumption can bring 2.68% environmental benefit. Similarly, in mining activity, reducing blasting pollution is an effective measure in diminishing the environmental pollution; analogy results could be obtained from Table 5. Especially, the effect of the variation in electricity consumption was the highest on human carcinogenic toxicity in which a 5% electricity reduction could decrease 5.05E-02 kg 1,4-DCB. In addition, the effect of changes in on-site emissions also greatly influenced all impact categories. By contrast, the variation in chemical consumption had a minor impact. It should be pointed out that the sensitivity calculation was based on the functional unit of one tonne copper sulphate ore mining and beneficiation process.

**Process optimization**

As reported in Fig. 6 in the “Process contributor to the key categories” section, for tailing pollution, cement used in tailing treatment has made great contributions to the global warming, ecotoxicity, and human toxicity. During the production process of the copper concentrate in this mine, part of the tailings entered the waste rock dump, part entered the tailing pond, and the others were mixed with cement for backfilling. It was found revealed that through purification and recycling, the waste rock dump and the tailing pond had a minor environmental impact, the use of cement in the backfilling process contributed to the most environmental pollution burden. In fact, cement paste backfilling (CPB) is a major method of processing tailings and is widely used in mines across China. In a majority of the past studies, the performance and price of backfill materials have been given priority, and the environmental impact has always been neglected. The backfill materials are usually made of the Portland cement, solid waste (such as waste rock, fly ash, tailing, and slag), and water composition (Zhou et al. 2020). However, in recent years, the research on filling pastes has been continuously improved. In the backfilling process, new backfill materials have been more widely selected to substitute for cement to mitigate environmental pollution. For example, recycled building materials (broken bricks, the recycled concrete aggregates, and recycled asphalt pavement) were utilized as substitutes for backfill materials (Rahman et al. 2014). Deng et al. developed a novel CPB using the gangue rocks, fly ash, quicklime, and ordinary Portland cement which
was much more environmental-friendly (Deng et al. 2017). In order to further quantitatively analyze the environmental impact of different backfill materials, the existing databases in the Ecoinvent database in SimaPro were utilized. Based on the actual practice, one tonne of Portland cement used in the backfilling process was respectively replaced with the following four backfilling materials in the following five scenarios: scenario a—cement (alternative constituents 6–20%), scenario b—cement (alternative constituents 21–35%), scenario c—ordinary Portland, scenario d—ordinary Portland (alternative constituents 6–20%), and scenario e—ordinary Portland (alternative constituents 21–35%).

Table 5  Sensitivity analysis of process contributors on the identified key categories

| Category                        | Chemical consumption (%) | Electricity generation (%) | On-site emissions (%) | Mining activity (%) | Tailing pollution (%) |
|---------------------------------|--------------------------|----------------------------|-----------------------|--------------------|-----------------------|
|                                 |                          |                            |                       |                    |                       |
| Global warming                  | 0.20%                    | 1.56%                      | 2.68%                 | 0.32%              | 2.82%                 |
| Terrestrial ecotoxicity         | 0.60%                    | 0.69%                      | 1.88%                 | 0.77%              | 2.72%                 |
| Freshwater ecotoxicity          | 0.45%                    | 1.15%                      | 1.95%                 | 1.30%              | 2.01%                 |
| Marine ecotoxicity              | 0.46%                    | 1.16%                      | 1.93%                 | 1.28%              | 2.01%                 |
| Human carcinogenic toxicity     | 0.35%                    | 2.03%                      | 1.16%                 | 0.90%              | 1.36%                 |
| Human non-carcinogenic toxicity | 0.51%                    | 1.06%                      | 1.99%                 | 1.31%              | 2.04%                 |
scenario d—cement (pozzolana and fly ash 11–35%), and scenario e—cement (pozzolana and fly ash 36–55%). The environmental impact analysis on key categories of different backfill materials is shown in Fig. 8. The scenario e has the greatest impact on the five environmental impact categories, especially in the global warming, which reduces the environmental impact by approximately 40.39%. Replaced with cement (alternative constituents 6–20%) has little effect on the total environment. The replacement effects of cement (alternative constituents 21–35%) and cement (pozzolana and fly ash 11–35%) are similar. Among them, the environmental impact reduced by approximately 22.06% in global warming. Therefore, the application of these new backfill materials provides new ideas for cleaner mine production in the backfilling process (Zhou et al. 2020).

In addition, the environmental impact of electricity generation cannot be ignored, mainly related to the air pollution generated by the coal-based power generation process (Parker et al. 2016). The sensitivity analysis in the “Sensitivity analysis” section indicated that a 5% reduction in electricity consumption resulted in an environmental benefit of 1.56% in the global warming category and 3.09% in the human toxicity category. In the past 5 years, although there has been a trend of decline, the coal-based power generation has retained at about 70% of the China’s total energy production. In order to achieve a further detailed quantitative analysis, the following four scenario assumptions were performed based on the China’s power structure (CEC 2016), the proportion of coal-fired power generation was replaced by hydropower (scenario 1), gas-fired power (scenario 2),

![Fig. 8 Environmental impact analysis on key categories of different backfill materials](image-url)

**Table 6** Environmental impacts on the key categories of the four scenarios

| Environmental categories | Unit                  | Basic scenario | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|--------------------------|-----------------------|----------------|------------|------------|------------|------------|
|                          | Value                 | Value CR(%)    | Value      | Value CR(%)| Value      | Value CR(%)|
| Global warming           | kg CO₂ eq             | 0.24           | 8.56E-02   | 64.63      | 0.143      | 40.91      |
| Terrestrial ecotoxicity  | kg 1,4-DCB            | 0.12           | 4.61E-02   | 60.93      | 3.82E-02   | 67.63      |
| Freshwater ecotoxicity   | kg 1,4-DCB            | 2.08E-03       | 8.13E-04   | 60.91      | 5.85E-04   | 71.88      |
| Marine ecotoxicity       | kg 1,4-DCB            | 2.93E-03       | 1.13E-03   | 61.43      | 8.34E-04   | 71.54      |
| Human carcinogenic toxicity| kg 1,4-DCB           | 6.66E-03       | 2.44E-03   | 63.36      | 1.06E-03   | 84.08      |
| Human non-carcinogenic toxicity | kg 1,4-DCB     | 5.09E-02       | 1.88E-02   | 63.06      | 1.49E-02   | 70.73      |

Note: CR, changing rate
nuclear power (scenario 3), and wind power (scenario 4), respectively. Table 6 presents the environmental impacts on the identified key categories of the four scenarios. As a whole, when the proportion of coal-fired power generation decreased, the overall environmental burden diminished. When coal-fired power generation was replaced by nuclear power, the environmental pollution on the global warming can be reduced by about 86.57%. The impact on human carcinogenic toxicity and freshwater ecotoxicity would be reduced by 84.08% and 71.88%, respectively, as the coal-based electricity generation was substituted by the gas-fired power. Therefore, it is crucial to improve energy efficiency and adjust energy structure for achieving cleaner electricity generation.

Conclusions

The normalization of midpoint results indicated that the marine ecotoxicity, freshwater ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, and terrestrial ecotoxicity were the major environmental impact categories. In addition, it was concluded that the mining activities, tailing pollution, and on-site emissions were the dominant contributions to the overall environmental impact. The further detailed analysis identified that the environmental impact of the blasting process in mining activities was the largest attribution. The adoption of cement in the backfilling activity of tailing treatment was the main source of tailing pollution (environmental pollution caused by the upstream cement production process was included). For on-site emissions, copper to air is the main substance affecting terrestrial ecotoxicity; zinc and chromium emission to water are the main substances influencing the freshwater ecotoxicity, marine ecotoxicity, and human toxicity. More importantly, the impact of chemical consumption on ecotoxicity could not be ignored, and the electricity generation was also regarded as the key process contribution. Finally, the sensitivity analysis revealed that adjusting electricity structure and reducing the pollution from backfill materials were crucial to solving environmental problems owing to the copper-sulfur mining and beneficiation process.

The findings obtained from this research provide realistic policy suggestions for effective decision-making in the copper-sulfur mine production and the entire metallurgical industry. Moreover, the LCI results are useful for improving the LCI database of copper-sulfur mine production.

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Data availability If any researchers need the original data of this manuscript, the authors agree to provide relevant information.

Declarations

Ethics approval and consent to participate Not applicable.

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