Life cycle assessment of artisanal small-scale kaolin mining and its associated health implications among miners

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Abstract

Artisanal and small-scale mining (ASM) is regarded as a means to enhance and uplift living standards in rural areas, often serving as the primary livelihood for local communities, however, the environmental burden associated with ASM cannot be ignored. Compared to other minerals, studies emphasizing the environmental and health impacts of kaolin mining and its beneficiation are limited. This research employed the life cycle assessment (LCA) tool to evaluate the environmental consequences and health problems associated with artisanal and small-scale kaolin mining (ASSKM) based on ReCipe 2016 Midpoint (H) and IPCC GWP 20a methods. Foreground data was collected from the mining site and the background data was accessed using the Ecoinvent v3 database. Standardized results showed a higher contribution of marine ecotoxicity, followed by human carcinogenic toxicity, freshwater ecotoxicity, and human non-carcinogenic toxicity. Contribution analysis revealed that electricity, diesel, and steel consumption contributed heavily among the above impact categories. Based on the sensitivity analysis results, the key measures to tackle environmental impacts involve improving kaolin beneficiation and mining operations. Among the health issues, musculoskeletal problems were recognized as the most affected problem encountered by miners followed by skin irritation and respiration problems however hearing loss and eye irritation showed lower scores. This study seeks the attention of stakeholders, environmentalists, policymakers, and licensing authorities, urging them to develop policies that promote environmentally sustainable practices in ASM within the region.

1. Introduction

Kaolin also referred to as china clay is a naturally occurring, soft, and pale clay substance that is mined from primary and secondary sedimentary deposits depending on their origin. Kaolin contains about 85% of kaolinite minerals and small amounts of mica, feldspar, illite, and quartz. Owing to its favorable physical, mineralogical, and chemical attributes, kaolin finds extensive use as a raw material in the manufacturing of ceramics, cement, paints, refractory bricks, tiles, papers, pharmaceuticals, toothpaste, fabrics, rubber, and plastics [1]. Kaolin is mined out by large-scale mining (LSM), small-scale mining (SSM), and artisanal and small-scale mining (ASM) operations. Large-scale mining operations are carried out with careful planning, advanced equipment, skilled labor, and technological breakthroughs [2] while SSM or ASM adapts manual labor and a less sophisticated approach to mining the resources [3]. ASM is being practiced acutely as a result of the increasing value of minerals both at the regional and worldwide scale with approximately 100–150 million people engaged in over 80 countries compared to only 7 million people in 2013 [4, 5]. Although ASM plays a crucial role in supporting the economic well-being of local communities, the environmental consequences linked to it should not be underestimated. The environmental impact of ASM primarily leads to negative outcomes, including adverse effects on human health, deforestation at mining sites, the discharge of mine tailings into groundwater sources, and degradation of ecosystems, as well as air pollution, dust, and noise [6, 7]. It is observed from the literature that the environmental impact studies have mainly emphasized LSM operations [8–11] thus leaving behind the gaps to assess the environmental footprints of ASM. In regions where ASM mining serves as the predominant source of livelihood, the lack of environmental evaluation can result in severe and devastating outcomes.

Besides, environmental problems and health and safety concerns arising from the mining sector cannot be ignored. Health and safety issues within the mining sector encompass a range of concerns, including ergonomic strains, accidents, noise pollution, child labor, mining-induced landslides, infectious diseases, and more [12]. Adverse effects associated with ASM include heightened aridity and dust levels, land use and landscape modifications, miners' exposure to occupational risks, and increased occurrence of diseases. [13]. Concerns regarding the health and safety of miners involved in kaolin mining within the context of ASM have not garnered sufficient attention. For example, Jiskani et al [14] investigated the severity of musculoskeletal disorders among coal miners. In another study conducted by Batool [15], the authors discussed the occupational and health issues focusing on the surface and underground coal mines. Similarly, hazard and safety assessment in underground mines was reported by [16, 17]. These research studies have only focused on the health and safety problems related to LSM, particularly, underground and surface coal mines. Considering previous research, there is a deficiency in studies examining the environmental and health effects on miners involved in both kaolin mining and its beneficiation within the context of ASM.

Life cycle assessment (LCA) is a reliable tool to comprehensively investigate the environmental impacts caused by any product, system, or service by quantifying the inputs and outputs linked to the particular process. In addition, LCA can provide useful insights about the mining industry [18] providing guiding effort in decision-making through sustainability reporting. The knowledge of LCA has been applied to evaluate the environmental footprints of minerals and metals such as coal mining [9, 10, 19], gold [20], copper [21], iron [22], zinc [23], cobalt [24], lead-zinc [25, 26], and other mineral industries [27]. However, minimal studies are present in the literature that assess the environmental impacts of ASM using LCA for example, sandstone mining [28], gold mining [29], mine tailings [30], and cobalt [31]. The study conducted on the LCA of kaolin investigates the environmental burden of metakaolin used as a cementitious material [32]. [33] studied the life cycle impacts of kaolin and calcium carbonate pigments for paper manufacturing focusing on the carbon footprints and did not provide any detailed environmental assessment based on the various impact categories. [1] assessed the radiological implications to health from kaolin mines and did not consider the health problems linked with the actual mining and processing of kaolin. Therefore, it is crucial to assess the environmental and health impacts resulting from ASSKM. This study aims to assess the environmental impacts emerging from the ASSKM by following the general guidelines of ISO 14040 [34]. This research develops the first life cycle inventory (LCI) for ASSKM operations at a geographical stage to cope with the deficiency in data availability. The current study has aspired to answer the research questions related to ASSKM such as what are the impacts of ASSKM on the overall environment? what are the key impact categories and their contribution to the ecological system? and how does ASSKM affect human health and the people linked with this occupation?

2. Research methodology

The LCA method using the Simapro 9.0.0 software package was applied to develop the LCA model. The ReCipe Midpoint (H) method is implemented to investigate the environmental impacts associated with ASSKM. This method is classified into 18 impact categories namely, global warming (GW), stratospheric ozone depletion (SOD), ionizing radiation (IR), ozone formation-human health (OF-HH), fine particulate matter formation (FPMF), ozone formation-terrestrial ecosystems (OF-TEco), terrestrial acidification (TA), freshwater eutrophication (FWEu), marine eutrophication (MEu), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FWEco), marine ecotoxicity (MEco), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), land use (LU), mineral resource scarcity (MRS), fossil resource scarcity (FRS) and water consumption (WC).

2.1 Background of the study area

The study area is in Nagar Parkar, a city in the Sindh Province, Pakistan situated around 400km southeast of Karachi. Kaolin deposits of economic significance are exclusively found in two locations within Pakistan: Shah Deri, Swat, KPK Province, and Nagar Parkar, Sindh Province [35]. The Geological Survey of Pakistan (GSP) initially documented the Nagar Parkar kaolin deposits in 1961, and they were subsequently subjected to comprehensive exploration studies conducted by the Pakistan Mineral Development Corporation (PMDC) between 1976 and 1979. The total estimated reserves of kaolin deposits in Nagar Parkar are 3.6 million tonnes [36]. These deposits were formed by the process of chemical weathering of Precambrian granite [35]. Kaolin deposits are typically found as sizable pockets or layers, often concealed by a layer of soil or a cap rock made of laterite. The thickness of these deposits ranges from 1.5 to 10 meters, with an average overburden thickness of 2.1 meters. These deposits are mined out by deploying ASSKM methods.

2.2 Kaolin beneficiation at the site

The study encompasses three primary stages: the mining of kaolin, its transportation to the processing plant, and the kaolin's enhancement through a beneficiation process. The initial phase involves the extraction of raw kaolin ore from the deposit situated approximately 28 km away from the beneficiation plant using an excavator machine of PC-250 model. Subsequently, diesel-powered trucks with a loading capacity ranging from 7 to 12 tons are used to transport the raw kaolin ore to the processing plant. The purpose of the beneficiation stage is to improve and enrich the quality of the raw kaolin ore by washing and removing unnecessary impurities ensuring its alignment with market demand [37]. The beneficiation process involves eight steps i.e., from the extraction of kaolin to its packaging as shown in Fig. 1. In the first step, the gathered raw kaolin is introduced into an agitation tank, where water is added to create a slurry using a spiral machine. The spiral machine's function is to homogenize and blend the mixture of kaolin and water. The washed slurry is subsequently subjected to screening using 250 mesh screens. The slurry containing undersized particles is channeled into open tanks to allow the particles to settle. Once the particles have settled, the water is pumped out, and the washed kaolin is stored in a separate tank. The washed kaolin is then directed to filter press machines to produce filter cakes. These filter cakes are laid out in the presence of sunlight for drying. Following this drying step, the cakes are broken into smaller pieces and packed into bags for transportation to various industries.

2.3 Functional unit and system boundary

For this study, a functional unit (FU) of 1 ton of washed kaolin at the beneficiation plant is selected to quantify the environmental impacts. In the LCA, the system boundaries delineate which processes should be incorporated and which should be omitted. The system boundary for the current study is presented in Fig. 2. The dotted box indicates all the processes considered in the system boundary. The processes outside the dotted box (exploration, development, reclamation and rehabilitation, and kaolin consumption) are exempted from this study. This is due to the reason that for ASSKM no extensive exploration and development preparation is required before the start of mining operations. The reclamation and rehabilitation stages are not considered as the site is reclaimed after its closure. For the kaolin consumption stage, data acquisition is unattainable because of the kaolin’s exportation to a different province.

2.4 Life cycle inventory (LCI)

Foreground and background data were used to develop the LCI for this study. The data related to kaolin mining, transportation, and beneficiation processes were acquired from the mining site. To get the foreground data, a questionnaire was designed and distributed among the mining personnel. In addition, interviews were conducted with the miners, and observations were made by visiting the kaolin beneficiation site in Nagar Parkar, a city in the province of Sindh, Pakistan. For the background data, the Ecoinvent database [38] was accessed together with the data from research articles, official reports from the government, and other published research. The LCI for this study is illustrated in Table 1.

While acquiring data from the kaolin site, some uncertainties may be found because some data is approximate and may contain some errors therefore, uncertainty analysis is carried out to improve the reliability of the data used for LCI. In uncertainty analysis, measured data is assumed to have a logarithmic normal distribution in the LCA, and the lognormal distribution is defined by a standard deviation. The lognormal distribution means that the square of the geometric standard deviation (GSD) has the coverage of a 95% confidence interval.

To examine the reliability (U_1), wholeness (U_2), temporal relationship (U_3), spatial correlation (U_4), technological relationship (U_5), and basic uncertainty (U_b) of the acquired data, data quality indicators were developed by [39] using a pedigree matrix to calculate the GSD^2. To calculate the uncertainty of the input and output data based on (U_1-U_5, U_b), Eq. (1) should be referred and the uncertainty results are presented in Table 1.

$$GSD^2 = \exp\sqrt{[\ln(U_1)]^2 + [\ln(U_2)]^2 + [\ln(U_3)]^2 + [\ln(U_4)]^2 + [\ln(U_5)]^2 + [\ln(U_b)]^2}$$

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Table 1
Life cycle inventory of ASSKM (values/functional unit)

Processes	Inputs	Quantity	Unit	GSD^2
Mining of kaolin	Kaolin ore	3.33	tonne	1.22
	Diesel	1.558	kg	1.32
	Carbon dioxide	0.977	kg	1.58
	Sulfur oxide	0.0117	kg	1.58
Transportation	Diesel	1.87	kg	1.32
	Truck	4950	tkm	2.03
	Carbon dioxide	5.874	kg	1.58
	Sulfur oxide	0.0044	kg	1.58
Kaolin beneficiation	Electricity	3.58	kWh	1.13
	Diesel	0.28	kg	1.32
	Groundwater	500	kg	1.13
	Drinking water	90	kg	1.13
	Heat	23.31	MJ	1.24
	Steel	0.347	kg	1.58
	Carbon dioxide	4.4991	kg	1.58
	Sulfur oxide	0.029666	kg	1.58
	Nitrogen oxide	0.0151	kg	1.58

3. Results and discussions

3.1 Energy usage and air emissions

ASSKM utilizes coal-generated electricity and diesel as an energy source to carry out the mining and processing operations. Electricity is mainly consumed in kaolin washing and diesel is consumed in the generators, tractors, and trucks for electricity and transportation.

Diesel fuel contributes to the emissions of CO_2. A considerable quantity of diesel is consumed in generators to wash the kaolin and in vehicles to transport kaolin from the mining site to the plant. Emissions from diesel consist of approximately 12% carbon dioxide (CO_2) and less than 1% of pollutant emissions, including carbon monoxide, nitrogen oxides, hydrocarbons, and particulate matter [40]. In contrast, emissions from coal-generated electricity primarily result in CO_2, nitrogen oxides (NO_x), and sulfur oxides (SO_x) emissions [40, 41]. This study has concentrated on carbon dioxide sulfur oxides and nitrogen oxides since only diesel and coal-generated electricity were utilized in the processes.

The emissions from the diesel fuel consumed in transportation are computed using diesel carbon content of 0.734 g per liter (2.778 g/gal) and an emission factor of 2.67 kg CO_2 per liter (10.1 kg/gal) of diesel (EPA, 2005). The calculation of CO_2 emissions during the processing phase involved applying an emission factor of 1.01 kilograms of CO_2 per kilowatt-hour (kWh) of electricity consumed [28]. Calculated results are presented in Table 2. SO_x emissions during mining and transportation are computed using Eqs. (2) and 1% sulfur content in Pakistani diesel (Yasin et al., 2012). The calculation of SO_x emissions during the processing are determined by using an emission factor of 8.25 kilograms per kilowatt-hour (kWh) of electricity consumed. The primary cause of NO_x emissions is predominantly linked to the utilization of coal-generated electricity in the processing phase. The estimation of NOx emissions is derived from an emission factor 4.22 kilograms per kilowatt-hour (kWh) of electricity utilized [28].

Table 2
Air emissions during kaolin mining, transportation, and beneficiation

Emissions	**Mining (kg/ton)**	**Transportation (kg/ton)**	**Beneficiation (kg/ton)**		**Total (kg/ton)**
			Diesel	Electricity	
CO_2	2.67×0.366= 0.977	2.67×2.2 = 5.874	2.67×0.333= 0.88911	1.01×3.58 = 3.61	11.32011
SO_x	0.366×0.001×64/32 = 0.0117	2.2×0.001×64/32 = 0.0044	0.333×0.001×64/32 = 0.000666	8.25/1000×3.58 = 0.029	0.045766
NO_x	-	-	-	4.22/1000×3.58 = 0.0151	0.0151
Where: Q_f = fuel use per kg, MW_P = molecular weight of pollutant emitted (64), EW_P = elemental weight of pollutant (32)					

$$SO_x = Q_f \times \text{ concentration of pollutant } \times \frac{MW_p}{EW_p}$$

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3.2 Life cycle impact assessment (LCIA)

To assess the environmental footprints, LCIA is performed based on elementary flows in LCI using the ReCipe midpoint and IPCC GWP 20a method. The impact categories were assigned to the inputs and outputs and the corresponding results were evaluated.

3.2.1 Characterization of the Results

Characterization includes the contribution of the processes respective to the midpoint categories. The results of the characterization using the ReCipe method are presented in Fig. 3.

The results are characterized based on three main processes involved in the processing of kaolin: extraction of kaolin ore (first process), transportation of kaolin ore (second process) to the processing plant, and kaolin beneficiation (third process). Referring to Fig. 3, the first process has a significant impact in only six categories including MRS on the top, followed by FRS, SOD, GW, and IR. The kaolin mining from the ore deposit has resulted in the MRS and the diesel consumption has caused the impact on other categories. The contribution of other categories was found insignificant. In the case of transportation, the higher environmental burden has resulted from FRS, SOD, GW, IR, and TA due to diesel consumption. Kaolin beneficiation has caused an ecological disturbance in almost all categories except FRS with comparatively less contribution.

To check the reliability of the results, the uncertainty analysis was carried out using Monte Carlo Simulation (1000 runs), and the confidence interval of squared geometric standard deviation was set at 95%. This means that 95% of the uncertain results acquired were within the range of dividing and multiplying the midpoint result value by squared geometric standard deviation. For instance, in the case of the mining of kaolin, the environmental impact on global warming was 5.744 kgCO_2 eq, and the related GSD^2 was 1.15. It demonstrates that the 95% confidence interval for global warming ranges between 4.994 kg CO_2 eq to 6.605 kg CO_2 eq. Table 3 shows the LCIA midpoint results.

From the characterization results, kaolin beneficiation has great environmental footprints as compared to the other two processes.

Table 3
LCIA midpoint results

Impact category	Unit	Mining of kaolin	Transportation to the processing plant	Kaolin beneficiation	GSD[2]
Global warming	kg CO_2 eq	5.744	6.894	16.252	1.15
Stratospheric ozone depletion	kg CFC11 eq	1.41E-06	1.69E-06	3.27E-06	1.13
Ionizing radiation	kBq Co-60 eq	0.0659	0.0791	0.215	1.14
Ozone formation, Human health	kg NO_x eq	0.00303	0.0036	0.0550	1.17
Fine particulate matter formation	kg PM2.5 eq	0.00350	0.0042	0.0625	1.14
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.00322	0.00387	0.0558	1.17
Terrestrial acidification	kg SO_2 eq	0.0107	0.0129	0.0852	1.16
Freshwater eutrophication	kg P eq	0.0001	0.00012	0.0122	1.16
Marine eutrophication	kg N eq	1.33E-05	1.59E-05	0.00075	1.16
Terrestrial ecotoxicity	kg 1,4-DCB	1.1367	1.3644	20.122	1.17
Freshwater ecotoxicity	kg 1,4-DCB	0.00783	0.0094	0.4808	1.14
Marine ecotoxicity	kg 1,4-DCB	0.01372	0.01647	0.6717	1.14
Human carcinogenic toxicity	kg 1,4-DCB	0.0178	0.0214	1.24006	1.19
Human non-carcinogenic toxicity	kg 1,4-DCB	0.24229	0.2908	23.963	1.14
Land use	m^2a crop eq	0.01028	0.01234	0.3809	1.20
Mineral resource scarcity	kg Cu eq	81.586	0.00169	0.07556	1.21
Fossil resource scarcity	kg oil eq	1.9278	2.3138	2.7808	1.14
Water consumption	m^3	0.00940	0.011285	0.6289	1.10

For results based on the IPCC GWP 20a, the highest contribution of emissions was witnessed in the kaolin beneficiation process (57.11%) due to the consumption of fossil fuel, and electricity consumption. Whereas, fossil fuel utilized in the transportation phase depicted comparatively less emissions (23.92%) than that of kaolin processing. Extraction of kaolin has the lowest environmental impact among all with about 18.96%.

3.2.2 Standardized results

From the characterized results, it is difficult to understand which impact category contributed heavily to the environment among all the impact categories. Figure 4 depicts the standardized results. The larger contribution was rendered by the kaolin beneficiation process in the midpoint categories: ME, HCT, FE, and HNCT. The impacts of other categories were negligible.

3.2.3 Contribution analysis

The purpose of contribution analysis is to explain further the results based on the specified impact categories. This analysis is differentiated into two types such as group contribution and contribution of substances. For the group contribution, all the processes in the system boundary are classified into sub-systems and processes to be examined, whereas, for the contribution of substances, the environmental burden related to various components is investigated to better understand the significance of the impact categories.

3.2.4 Contribution of sub-systems and processes

In the contribution of sub-systems and processes, the share of sub-processes connected to the main processes is quantified to provide directions toward the cleaner transition of mineral production. The sub-processes are classified into six clusters: mining activities, ore processing, energy consumption, transportation, and waste treatment. Figure 5 presents the impacts of 5 sub-processes on midpoint categories. Mining activities have a substantial contribution to the GW and MRS whereas FPMF and TA have a negligible effect on the environment towards this process. Ore processing has a significant impact on TEco, FWEco, MEco, HCT, HNCT, and water consumption only. Energy consumption has a great environmental impact among all categories including FRS, LU, MEu, FWEu, TA, OF-TEco, FPMF, OF-HH, SOD, and IR. The effect of other categories was also large but low as compared to these categories. WC has a significantly lower contribution to the energy consumption process. As compared to other categories, the transportation process has a significant impact on GW, TA, and LU only. The waste treatment process has little contribution in the GW category only.

3.2.5 Contribution of substances to key categories

Based on the standardized results, key impact categories are identified and Fig. 6 illustrates the substance contribution to these categories. It can be observed that electricity consumption is the main cause of FEco, MEco, HCT, and HNCT accounting for 57%, 56%, 35%, and 34% respectively. Kaolin beneficiation heavily depends on electricity consumption thus resulting in the above environmental footprints. Diesel consumption has a share of about 25%, 26%, 27%, and 53% in the above four impact categories respectively. Diesel is mainly consumed in the transportation of dumpers and tractor machines. The consumption of steel has affected HNCT accounting for 37% however its effect on other key categories was considerably low. The filter press machine mainly used steel as a material as there were 3 filter presses installed on the site. Transportation using tractor machines has negligible influence on these categories.

3.2.6 Sensitivity analysis

Sensitivity analysis is performed to identify the most effective method, process, or component to reduce the environmental burden. The input parameters of the different processes under key impact categories were reduced by 5%, and the corresponding results were acquired. The results of the sensitivity analysis are presented in Fig. 7. When reduced to 5%, the kaolin beneficiation shows environmental effectiveness in all the key impact categories accounting for approximately 4.8% efficiency. As compared to kaolin beneficiation, extraction of kaolin and transportation stage showed very little share with less than 1% in all the categories. The impact on the environment was mainly reduced in the process of kaolin beneficiation because this process has utilized greater consumption of electricity, diesel, and steel as compared to other stages.

4. Survey

A total of 50 workers were involved in the mining and processing operation however at the time of study only 48 workers were available. In Nagar Parkar, numerous open pits have been dug to extract kaolin and each of them has separate washing plants [35]. This study is limited to one quarry site and its associated washing plant due to challenges in data collection. The number of miners may seem small but the workers' health condition from one washing plant can be representative of other plants as well due to the similar material, mining, and processing activities. A questionnaire was designed and distributed among the miners specifying the information about their education, miners' age, experience in mining, other than mining, marital status, health impacts, and affected health.

4.1 Demographic information

This section presents the demographic data of miners to find the relationship between demographics and health issues. It can be seen in Fig. 8 (a) that the majority of miners have an age ranging from 15–45 years. The workers affiliated with the age group of 31–35 and 36–40 years are high in number with approximately 31% and 25% respectively. The proportion of workers involved from other age groups is considerably small. To get information about the workers' experience related to mining and other than mining, data is presented in Fig. 8 (b). It shows that 12 out of 48 workers have 2 to 5 years of experience in mining whereas 20 workers have experience in other occupations. In the category of workers having experience of 5 to 10 years, 42% accounted for having mining experience while only 6% had other than mining experience. When interviewed, the majority of the workers responded that they worked as laborers in the construction of buildings before working in kaolin mining. This is because most of the workers belong to the local area and until they get employment in kaolin mining, they need to travel to other cities to earn money and help their families financially. It was found that only 15% of workers had 10–15 years of mining experience. It is also observed that before working as a miner, almost all the workers had worked in other occupations.

The educational information of the miners is shown in Fig. 9 (a) to check the influence of their qualification level on the work. The educational level of workers shows that 44% of workers have got the matriculation followed by 25% of workers having education in primary and middle school whereas only 6% of workers have cleared the intermediate exam.

The data on marital status is presented in Fig. 9 (b). A great number of individuals are married approximately 79% and unmarried accounted for only 21%. The workers aged between 26–30, 31–35, and 36–40 are married with proportions of 17%, 25%, and 23% whereas other age group workers have low scores. The unmarried workers' proportion is comparatively smaller than those of married with 8% and 6% affiliated with the 21–25 and 31–35 age groups respectively.

4.2 Impact of ASSKM on human health

To assess the health issues among miners, interviews were conducted with every individual miner working at the kaolin mining and processing site. The health status of the workers before employment and after employment based on the optimal and affected categories were examined. In the optimal category, around 69% of the workers reported that their health status was good before they started working at the kaolin plant which was reduced to about 38% after they started working at the mining site. In the affected category, 31% of miners reported that their health status was good before working but after their employment, a significant rise was witnessed showing the health affected at about 62%. The findings indicate a notable impact on the miners' health conditions once they commenced working at the kaolin mining site.

To further investigate the health issues of the miners, Fig. 10 illustrates health problems resulting from the mining activity. During the survey, miners highlighted the five major health problems encountered (respiration, musculoskeletal, skin irritation, eye irritation, and hearing loss). Among them, musculoskeletal issues (muscle pain, back pain) were at the top followed by skin irritation and respiration issues with around 73%, 67%, and 62% respectively. It is important to note that, the excavation of kaolin did not involve any physical workout by the workers because the kaolin ore was excavated with the use of machines. However, despite the availability of mining machinery at the kaolin processing site, the miners also had to rely on their physical strength to remove the kaolin cakes from the filter press machines, and pack and lift them through tiring effort resulting in musculoskeletal problems. As the miners had to work and deal with the wet china clay, throughout the day, skin issues were observed to be higher including skin irritation, and skin dryness. Respiration issues witnessed among workers were mainly due to the inhalation of dust particles produced at the kaolin site. However, only limited miners reported the problem of eye irritation and hearing loss with approximately 37% and 32% respectively.

5. Environmental and health implications

ASSKM mainly constitutes three stages: mining of kaolin, transportation of ore to the processing plant, and the beneficiation of kaolin. Among the characterization results (Fig. 3), MRS showed a greater contribution (99.90%) in the mining of kaolin due to the ore extraction. The transportation stage is influenced by the FRS (34.07%) as a result of fuel consumption. Kaolin beneficiation was affected by the water consumption category due to the large quantity of water usage (97.02%) for kaolin washing. From the group contribution results, environmental impacts caused by the sub-processes were identified, and based on this research these categories are accountable for the ecological damage which needs to be taken seriously in future studies. Based on the standardized results, the substance contribution to the key environmental impact categories was presented. Coal-generated electricity, diesel, and steel consumption affected almost all the key categories. The kaolin project utilizes electricity generated from coal due to its predominant role in Pakistan's energy generation with about 66% share [42]. Renewable energy sources, particularly solar and wind, have also gained momentum, contributing to the diversification of Pakistan’s energy mix. According to [43], Pakistan possesses substantial solar energy potential that can be harnessed to meet the growing electricity demand. The World Bank also reports that Pakistan has a potential of 40 GW of solar power and has set a target of achieving 20% of its electricity from renewable sources by 2025 [44]. Keeping in view the renewable energy potential and to better understand the environmental impacts emerging from different energy sources, the consumption of coal-generated electricity is replaced with solar-generated electricity in the kaolin production process as shown in Fig. 11. As compared to coal-generated electricity, the environmental impacts from solar-generated electricity have reflected positive outcomes in almost 9 categories except for SOD, LU, MRS, FRS, and WC with considerably very less proportion. As the electricity is mainly consumed in the kaolin washing stage thus are no significant benefits towards these categories. Electricity when replaced by solar energy, showed higher ecological benefits in FEu, MEu, FPMF, and TA with about more than 50%. Particularly, MEu and FWEu accounted for about 81% and 78% reduction in the impacts. The GW category represented about 28% less environmental burden as compared to coal-generated energy. It is important to note that the use of solar energy showed around 4% and 20% more environmental burden in IR and TEco categories when compared with coal energy.

The detrimental effects of mining industries on global warming, human health, and ecosystems stem from the consumption of fossil fuels [45]. Therefore, the integration of solar energy systems in the mining industry could be useful in reducing the environmental loads. The environmental footprints linked to steel consumption can be made effective by optimizing the use of steel along with recycling the waste steel [46]. Sensitivity analysis provides direction to the policymakers and stakeholders to decide on making the process environmentally efficient by reducing the identified impacts. The results from this research can help environmental agencies to be vigilant and make policies against the impacts resulting from the ASSKM.

Pakistan's mining sector is primarily characterized by the prevalence of numerous artisanal and small-scale mines [47]. These local mining practices have significant detrimental effects on mineral deposits, posing substantial health and environmental risks to the workforce. Keeping this in mind, the health problems from ASSKM are also discussed and it is found that the kaolin beneficiation stage resulted in health problems among miners. The problems encountered by the workers are musculoskeletal disorders, skin irritation, and respiration issues. The extraction of kaolin does not involve laborers relying on their strength to mine out the kaolin due to the availability of machines, however, the washing process of kaolin results in the above-mentioned health problems. The miners have to take out the filter cakes from the filter press and pack them manually under the sunlight. Lifting the bags full of kaolin cakes and placing them on the site also causes musculoskeletal problems because workers have to rely on their physical fitness. The dust generated by the kaolin leads to respiratory issues, including breathing difficulties, among the workers. Inhaling fine dust particles has resulted in silicosis, which is an incurable lung disease [48]. The workers have also encountered skin allergies due to their exposure to the kaolin material. While hearing loss and eye irritation issues are observed, their impact is significantly less pronounced. [28] have carried out a study on the LCA and health problems of ASM in sandstone. They reported musculoskeletal, respiration, and skin problems among miners. The findings of this research correspond with their results concerning musculoskeletal and respiratory issues. Nevertheless, it is worth noting that the current study observed a roughly 27% higher incidence of skin irritation problems. The mining industry's growth in Pakistan has been hampered by inadequate investment and a dearth of technological advancement [49]. The mining industry should persist in its endeavors to attain a more comprehensive outlook on its sustainable practices, encompassing safety, environmental, economic, operational efficiency, and community aspects. Good governance, when effectively implemented, is expected to significantly enhance the contribution of mineral resources to sustainable development. [50]. This study provides valuable insights for artisanal miners, public policymakers, and the wider community, facilitating the development of environmental management strategies, policies, and regulations aimed at minimizing the environmental impacts associated with ASSKM. Implementing mechanized mining processes to decrease labor-intensive work, following health and safety protocols, and adopting renewable energy sources can significantly improve the environmental and health aspects of ASSKM.

6. Conclusion

This research study assesses the environmental impacts of ASSKM and its associated health problems among miners in Nagar Parkar city of Sindh Province. LCA tool with ReCipe 2016 Midpoint (H) and IPCC GWP 20a is used to quantify the environmental burdens. The results of midpoint impact categories with uncertainty analysis have been investigated. Standardized results show a higher contribution of marine ecotoxicity, followed by human carcinogenic toxicity, freshwater ecotoxicity, and human non-carcinogenic toxicity. The group contribution results reveal that energy consumption, ore processing, and mining activities are the key processes causing environmental burden. Among them, consumption of electricity is highest at about 57% in freshwater ecotoxicity and 56% in marine ecotoxicity. Diesel consumption has contributed to human non-carcinogenic toxicity by about 53%. However, steel usage contributes significantly to human carcinogenic toxicity with a 37% share. Based on IPCC GWP 20a method, the environmental burden is mainly influenced by kaolin beneficiation (54.11%) followed by transportation (23.92%) and mining of kaolin (18.96%). Based on the sensitivity analysis findings, the key measures to tackle environmental impacts involve improving kaolin beneficiation and mining operations. Among the health issues, musculoskeletal problems are recognized as the most affected problem with a share of (73%) followed by skin irritation (67%) and respiration problems (63%) however hearing loss and eye irritation show lower scores. The results reveal that the environmental impacts in ASSKM can be optimized by reducing pollutant emissions followed by adopting renewable energy resources, technological development, and sustainable mining practices. The research proposes the formulation of strategies focused on legitimizing ASM practices in the region. This involves legalizing mining activities by issuing licenses to companies, ensuring that both the environmental impact of ASM and the financial well-being of local individuals engaged in the mining sector are safeguarded without compromise.

Declarations

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Author Contribution

This manuscript is a result of the collaboration of all co-authors. Muhammad Burhan Memon: Conceptualization, Writing- Original draft preparation, Methodology, Formal analysis; Ming Tao: Supervision, Project administration, Resources; Zheng Yang: Writing- Reviewing and Editing; Xingyu Wu: Investigation, Writing- Reviewing and Editing; All authors have read and approved the final manuscript.

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Figures

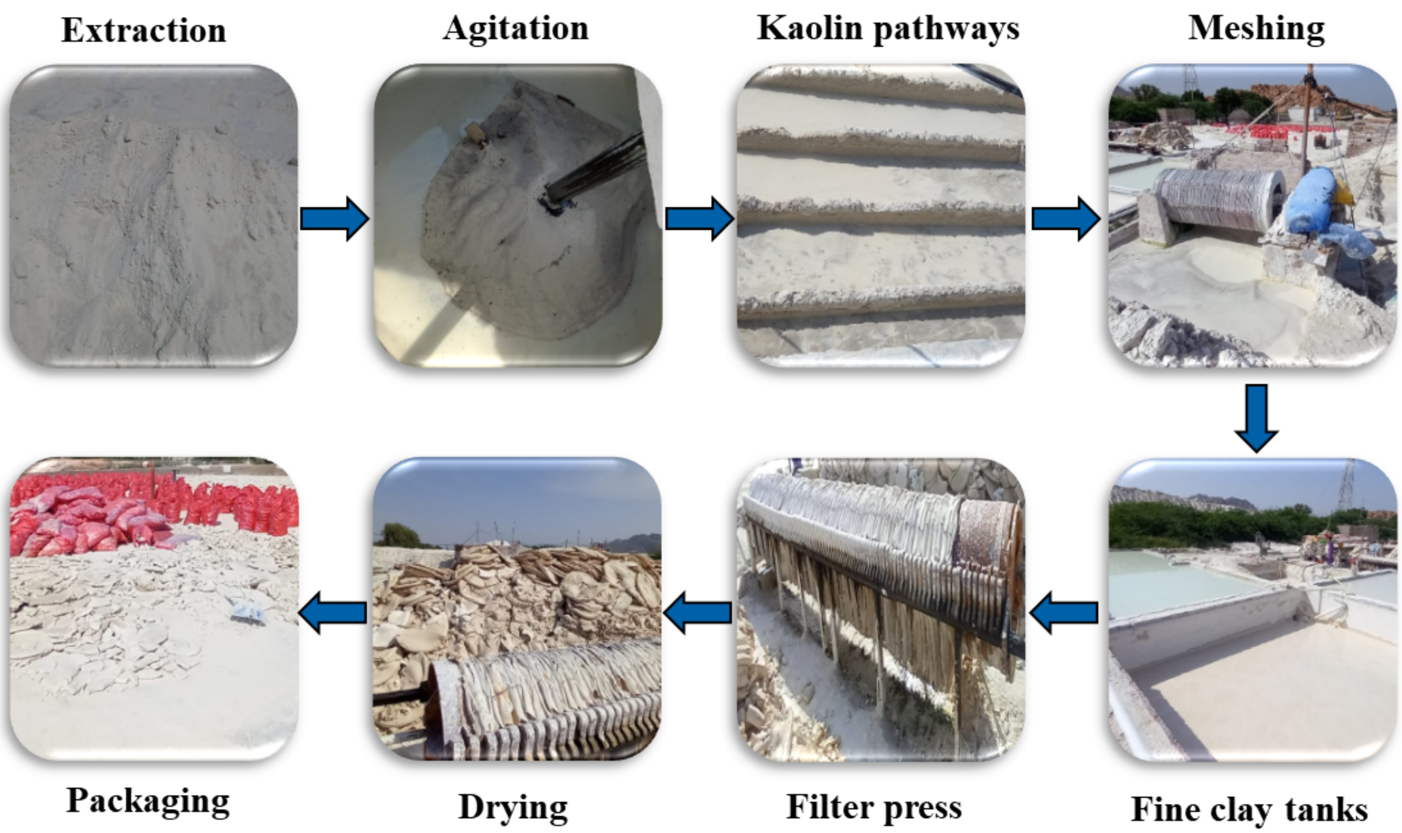

Figure 1

Kaolin beneficiation

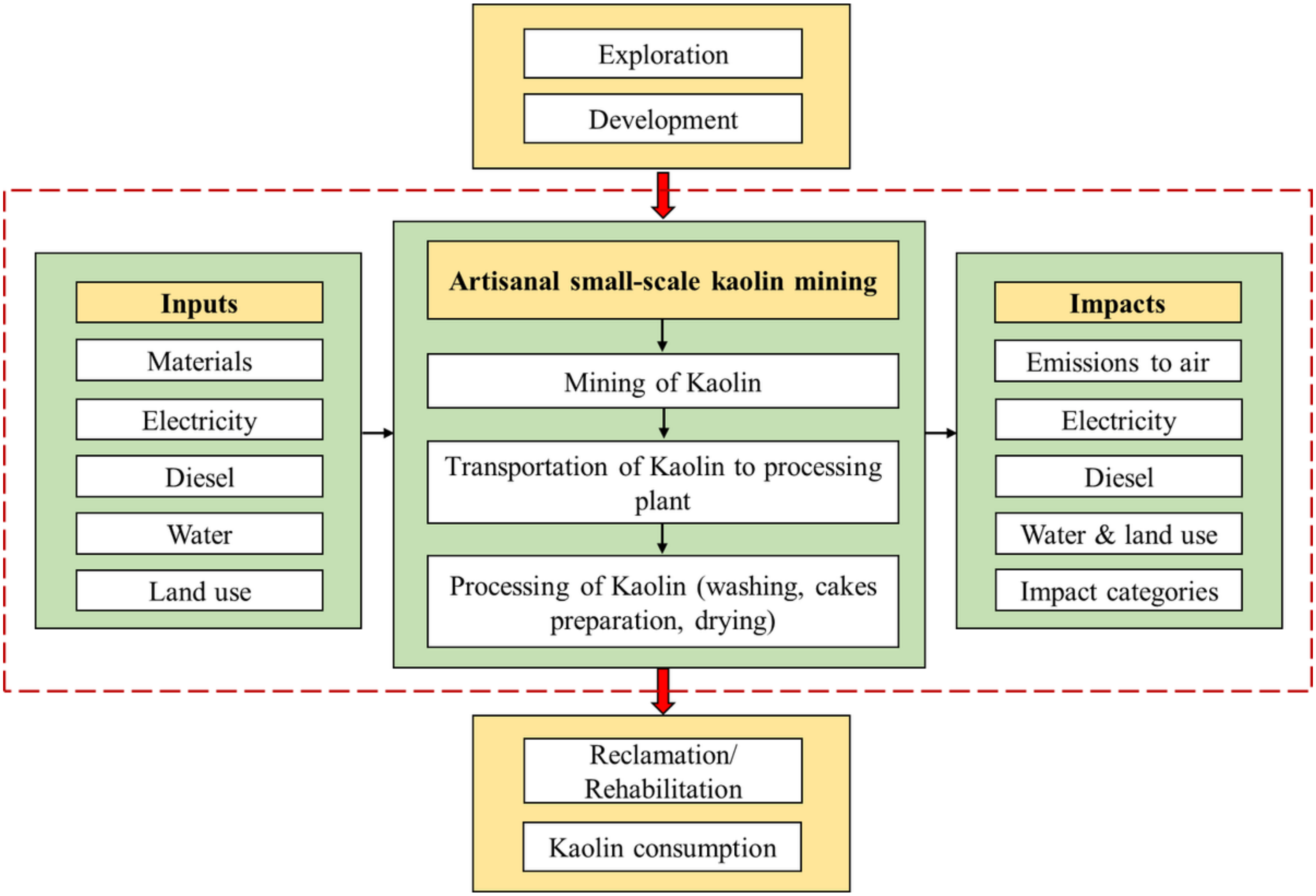

Figure 2

System boundary for the study

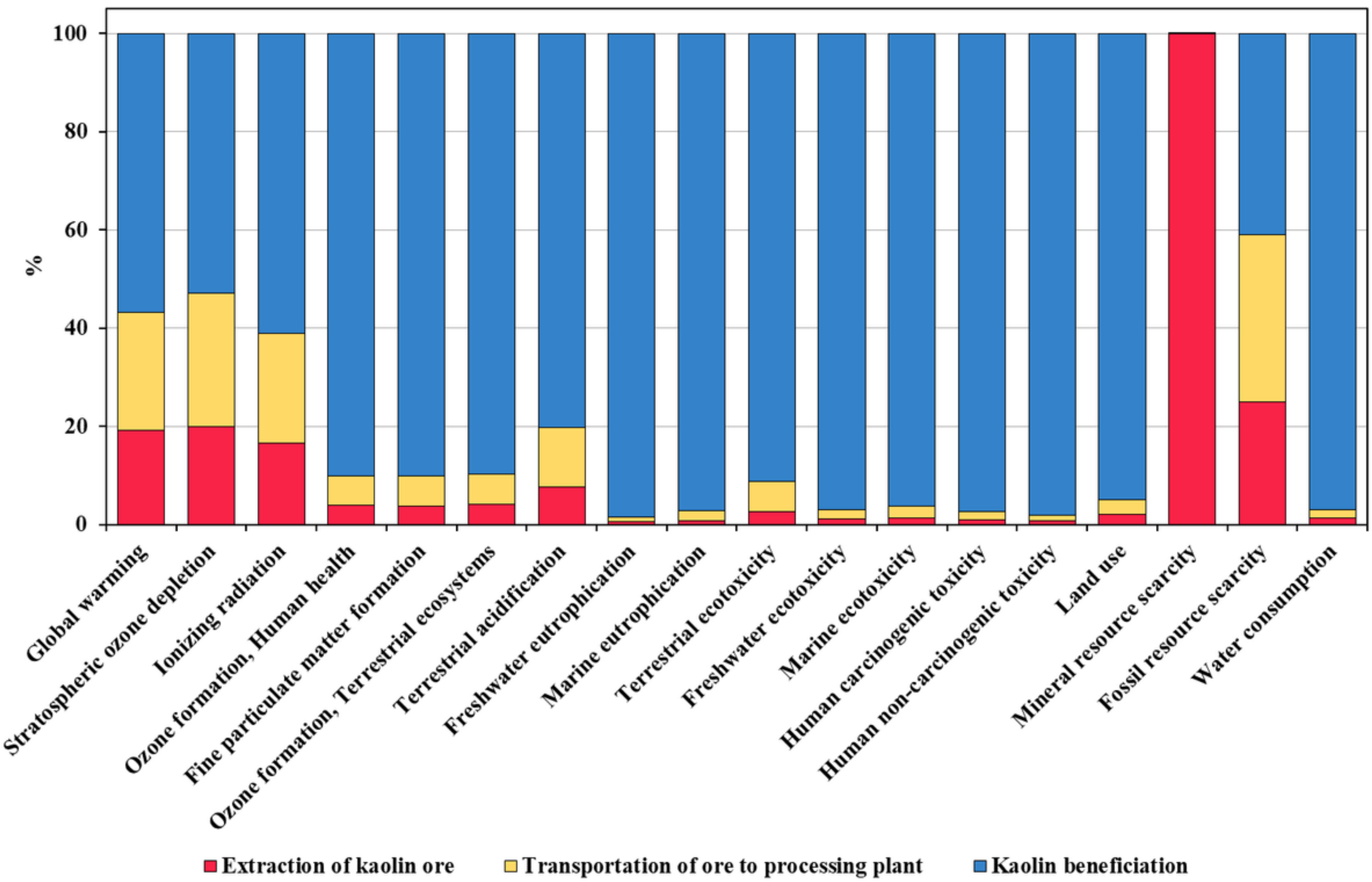

Figure 3

Characterized results based on ReCipe method

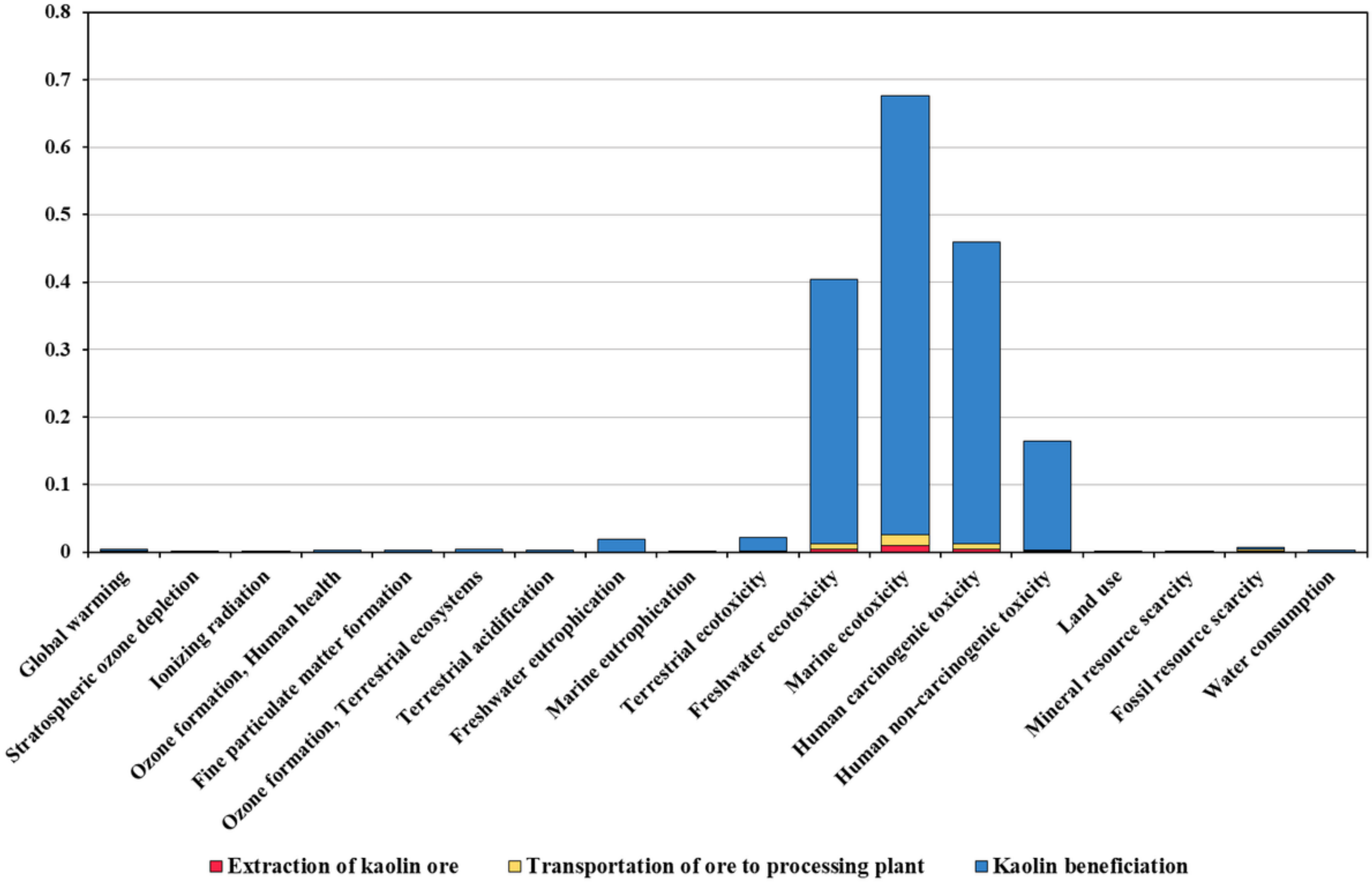

Figure 4

Standardized results

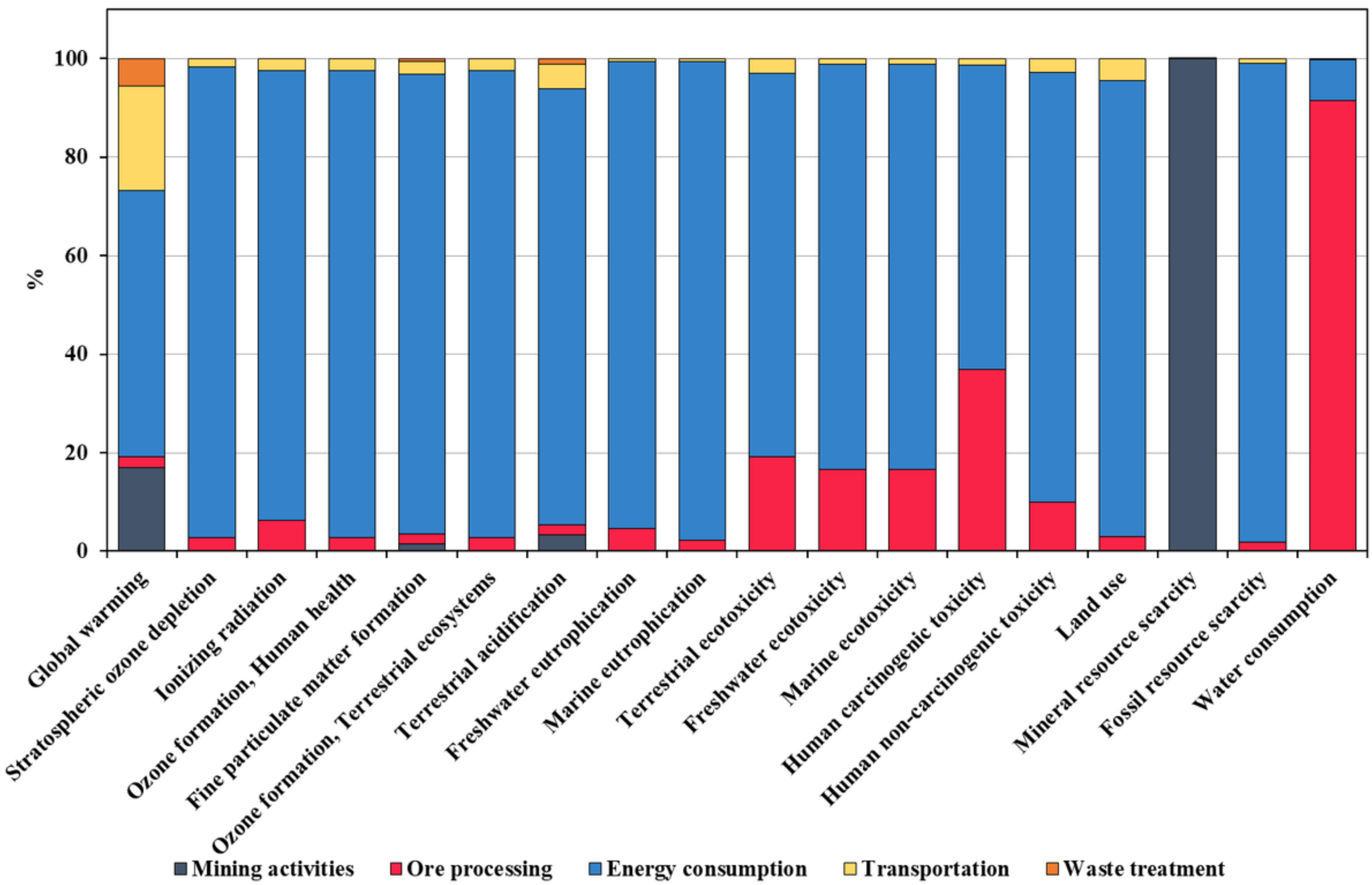

Figure 5

Contribution analysis of sub-processes

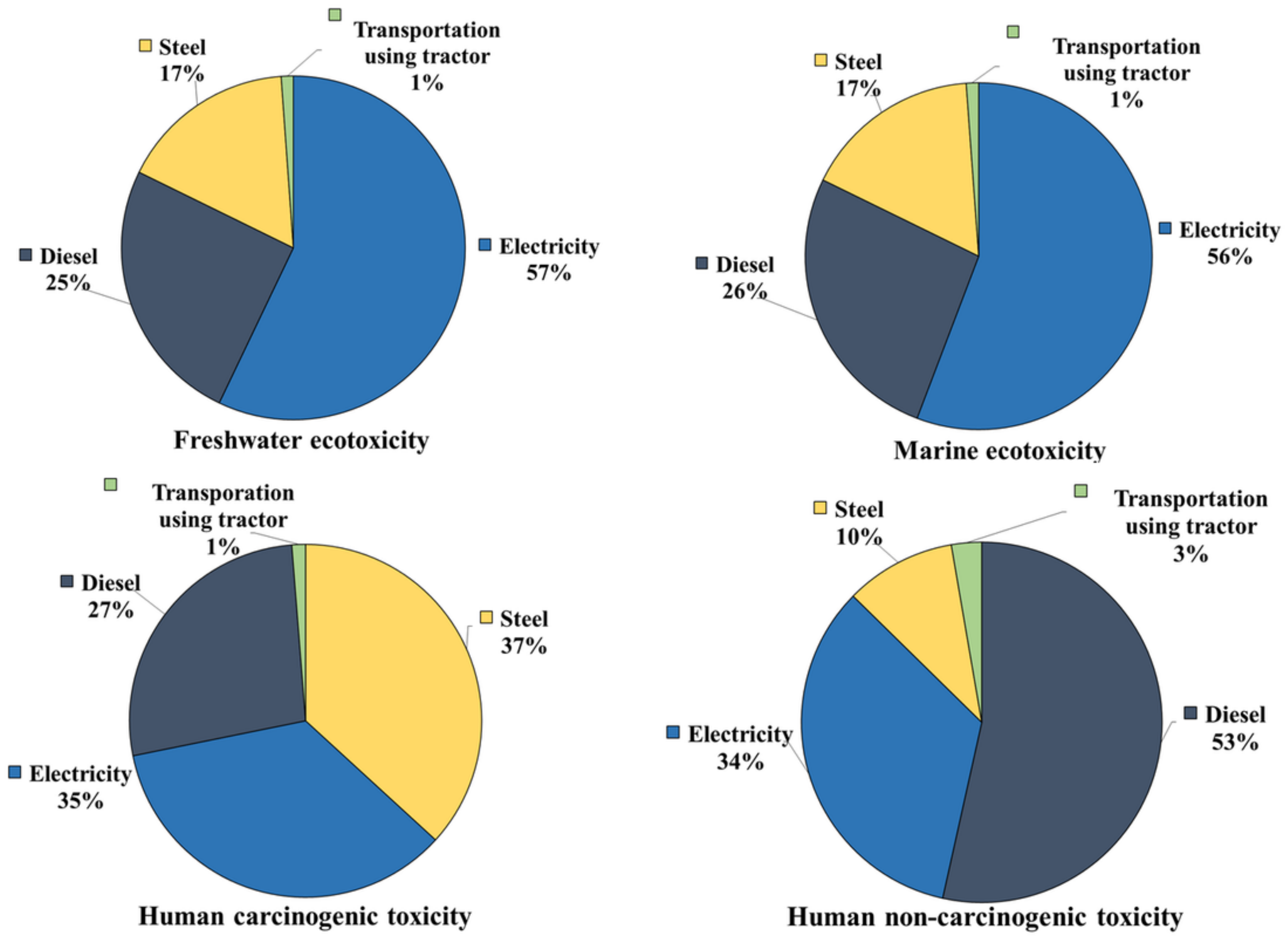

Figure 6

Contribution of substances

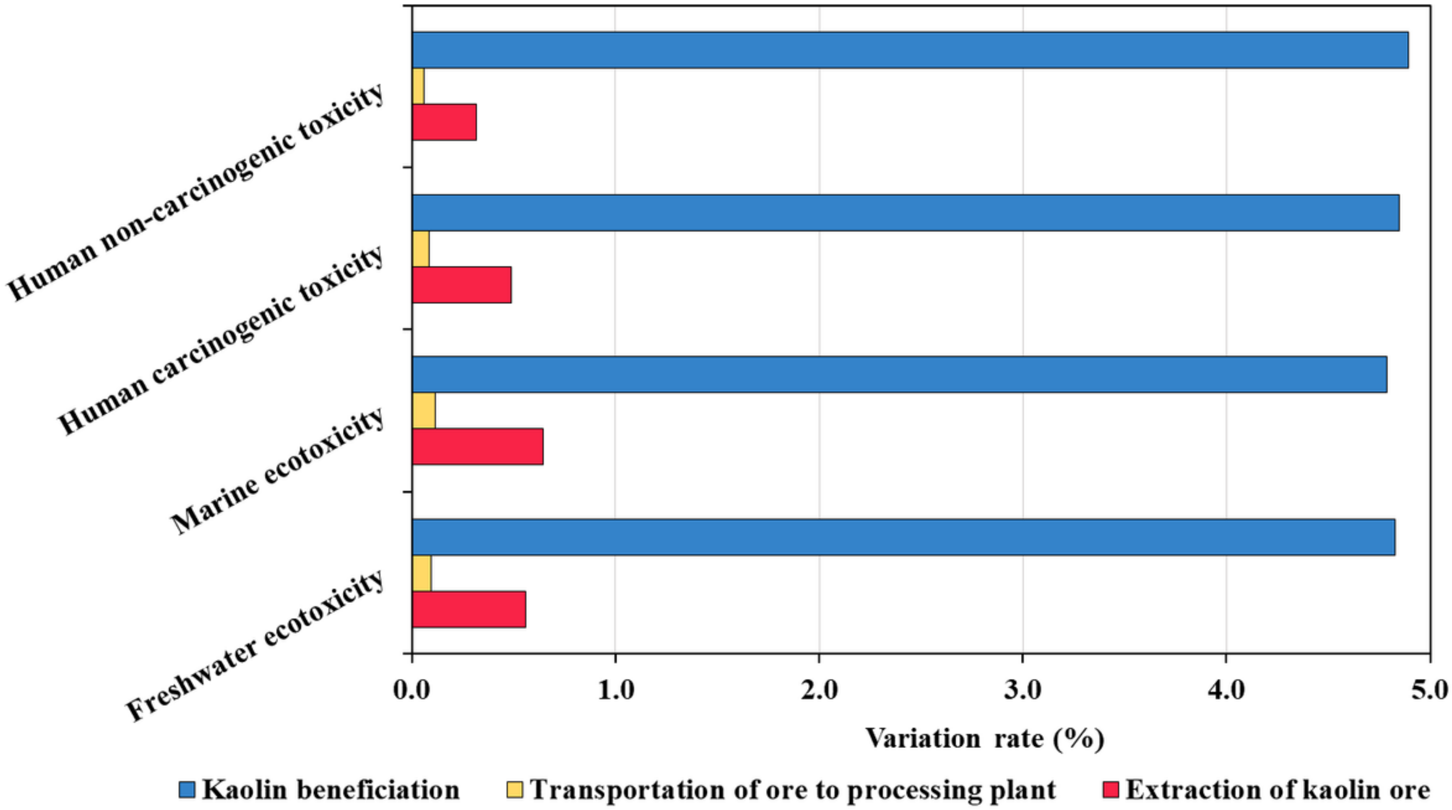

Figure 7

Sensitivity analysis

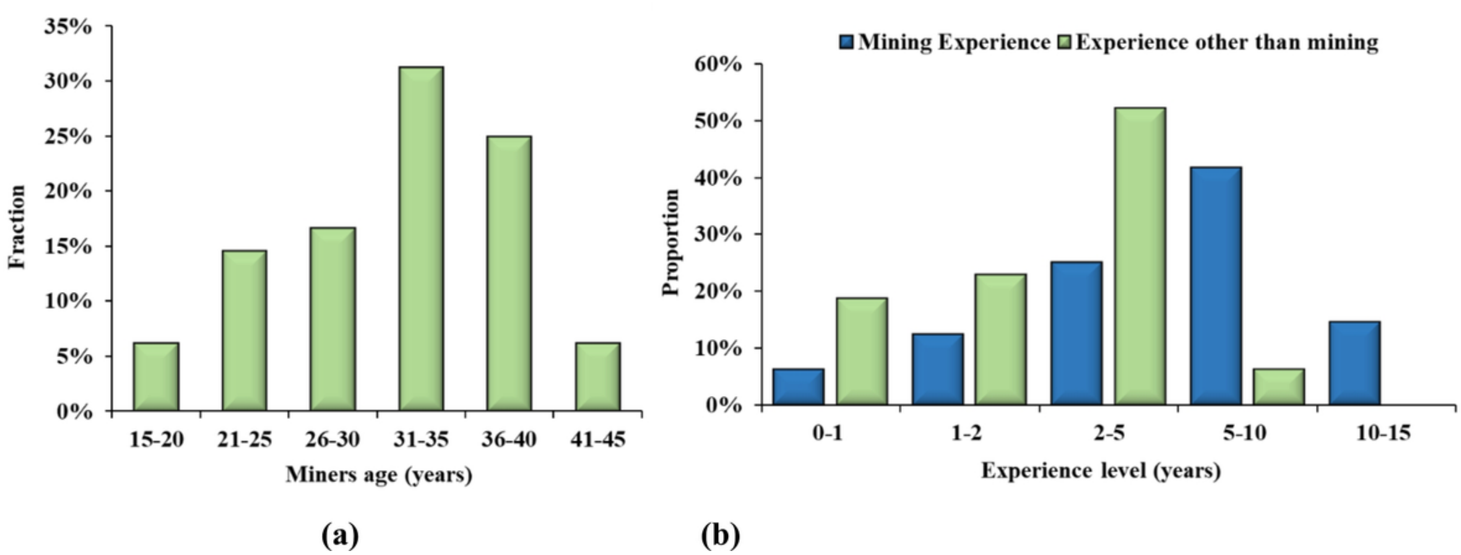

Figure 8

(a) Age of miners; (b) level of experience

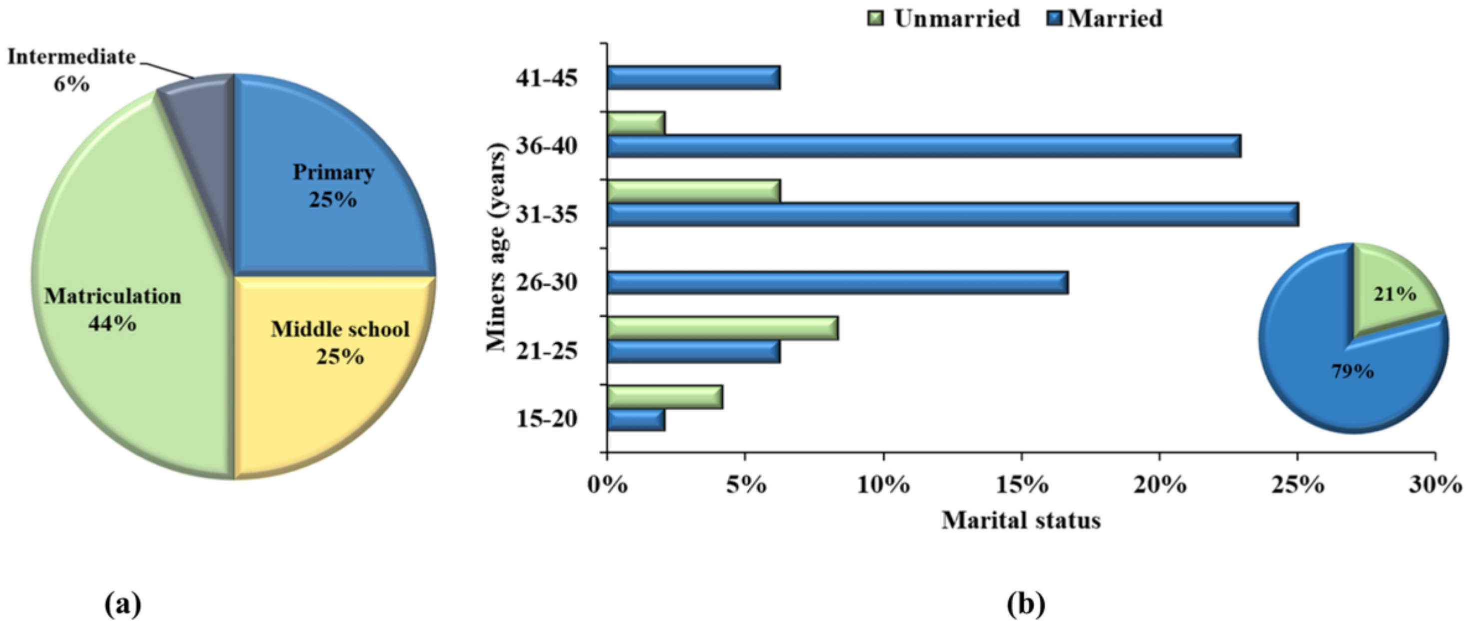

Figure 9

(a) Educational background of miners; (b) Marital status concerning different age groups

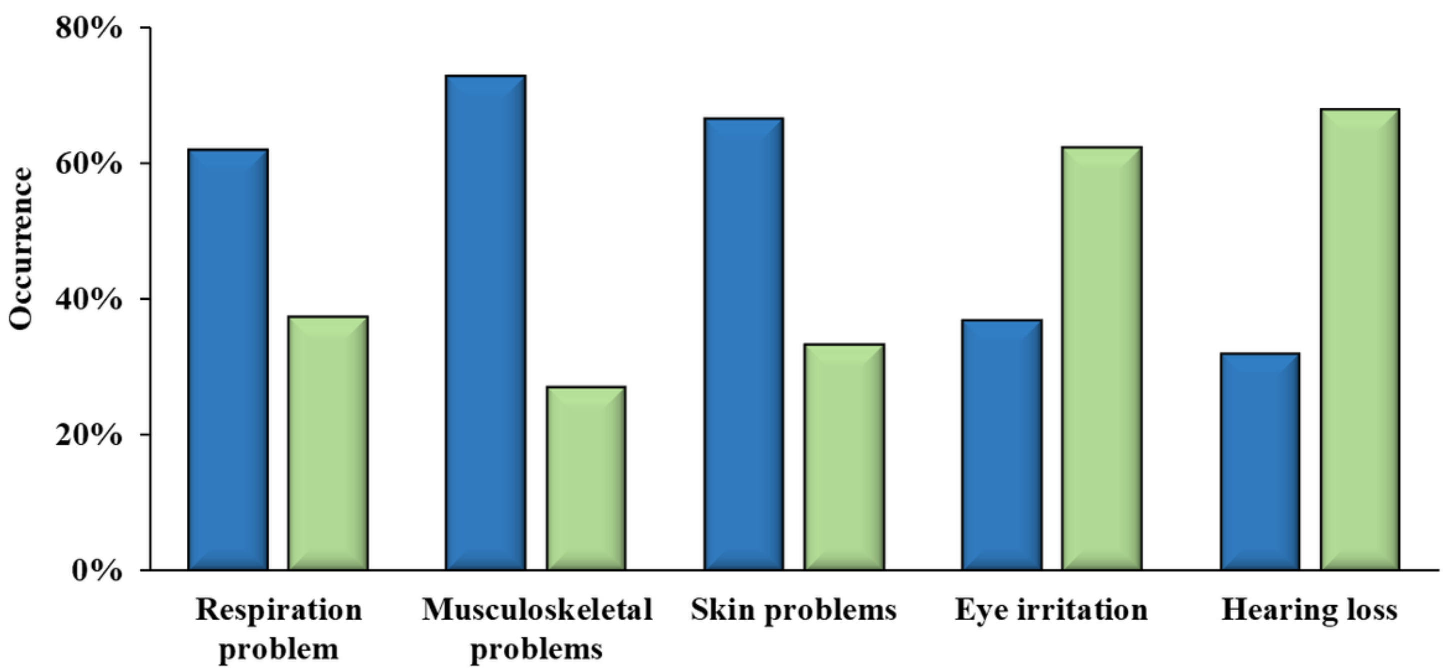

Figure 10

Health problems among miners

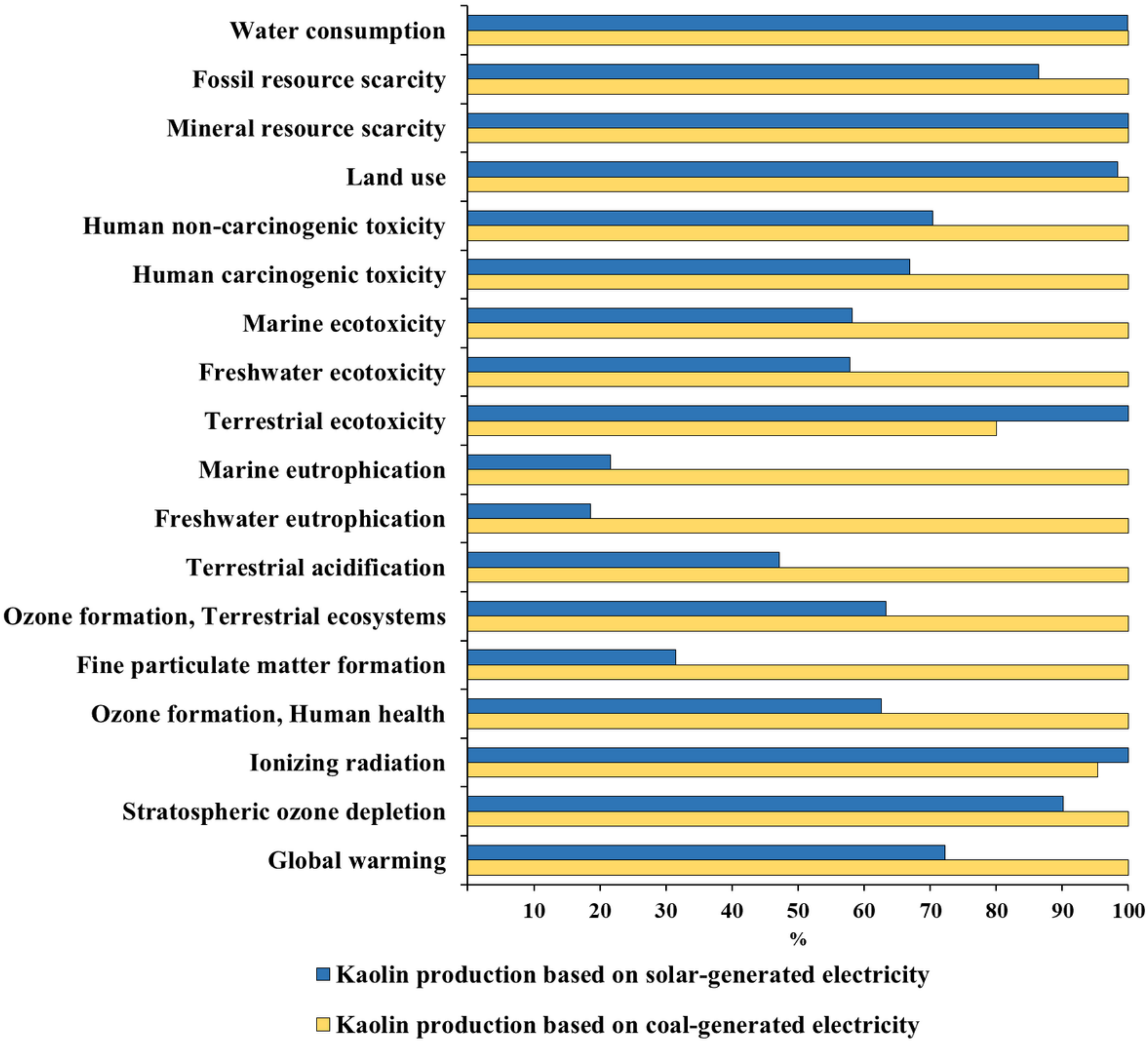

Figure 11

Kaolin production and beneficiation based on coal and solar-generated electricity