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Life cycle assessment of underground coal mining in China

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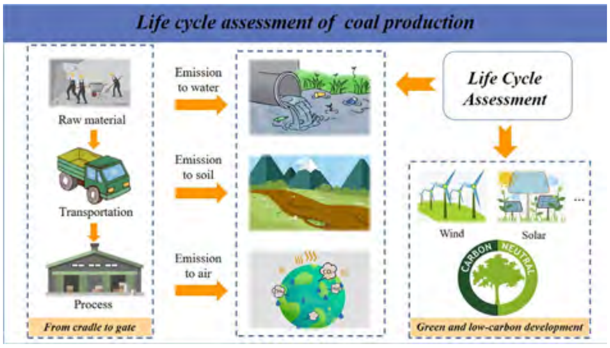
HIGHLIGHTS

- LCA was conducted on coal production of a typical coal mine in China.
- Key environmental impact categories and key impact processes were determined.
- Monte Carlo method was used to calculate the uncertainty of the results.
- Gas extraction brought about 24% environmental benefits to the climate.

GRAPHICAL ABSTRACT



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ABSTRACT

Coal is not only the main fossil fuel in China but also a pollution source. To evaluate the impact of coal production on the environment, a life cycle assessment (LCA) was conducted on the mining process of a typical coal mine in China by using the SimaPro 9.0.0 software. The Ecoinvent v3 database was used to provide the background data, and midpoint results with uncertainty information were calculated using the ReCiPe Midpoint (H) method. After normalising the midpoint results, fossil depletion was identified as the most predominant environmental impact category, followed by marine ecotoxicity, freshwater ecotoxicity, climate change, freshwater eutrophication, and human toxicity. The contribution analysis indicates that coal mining activities, consumption of steel and electricity, and mine ventilation are the key processes causing the above-mentioned environmental impact categories, which should be paid special attention. According to the sensitivity analysis, the primary countermeasures for addressing the environmental issues are to reduce the mining activities and improve the efficiency of coal mining and utilisation. In addition, the quantitative and comparative analyses show that the gas extraction production mode is beneficial to the environment. Finally, technical measures were proposed to promote green and sustainable development of the coal industry. This research can provide guidance for ensuring national energy security and promoting healthy development of the national economy.

1. Introduction

Since 2012, the annual output of raw coal in China has remained at 3.41 to 3.97 billion tonnes (SCIO, 2020). In 2020, coal accounted for 56.8% of the primary energy consumption (NBSPRC, 2021). In the next five years, coal is still expected to account for more than half of the primary energy consumption in China. It is estimated that by 2025, the coal

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consumption will be approximately 4.1 billion tonnes, accounting for approximately 52% (Kang, 2019). With the implementation of reforms in the energy structure, the proportion of coal consumption in China has declined, but the coal-based energy structure is expected to remain for a long time (Yuan et al., 2016). This huge energy consumption will result in a series of environmental problems, seriously threatening the ecological environment and human health.

Life cycle assessment (LCA) is an effective tool for quantifying product sustainability. Because it can quantitatively describe the burden of production on the environment (ISO 14040, 2006), it has been widely used in the industrial, agricultural, and other fields, as indicated in the studies by Nabavi-Pelesaraei et al. (2019), Khanali et al. (2021), Hou et al. (2016), and Saber et al. (2021). These studies have provided important theoretical support for sustainable development. By reviewing the literature, it was found that most LCA studies on coal focused on the consumption scenario, and there were only few studies concerning production processes. Peng et al. (2021) adopted the LCA method to assess volatile organic compound emissions from coal-fired power plants in China. Tong et al. (2021) conducted a LCA on three different technical coal-to-liquid routes. Li et al. (2019) studied the impact of greenhouse gases on the life cycle of direct chemical recycling of coal for hydrogen production. Some scholars have analysed the environmental pollution caused by coal tailings (Adiansyah et al., 2017; Peng et al., 2020). The above-mentioned studies obtained many useful conclusions. Because coal production is the second largest source of emissions after coal consumption (Aguirre-Villegas and Benson, 2017), the environmental pollution due to coal production cannot be ignored.

The application of the LCA method to assess the environmental impact of production processes is also of great significance. Some scholars have used the LCA method to comprehensively study the impact of greenhouse gases released from coal production on climate (da Silva et al., 2018; Korre et al., 2019), which has instructional significance for slowing down global warming. The impact of coal production on the environment is diverse (Pandey et al., 2014; Silva et al., 2013; Xu et al., 2017), but these studies only focused on the impact of climate change. Therefore, the overall impact cannot be completely reflected. Ghadimi et al. (2019) combined a fuzzy inference system with LCA and proposed an environmental performance index based on coal consumption and energy production (CCEP) to analyse the entire coal energy chain in China from coal preparation to transportation and subsequently to combustion. However, this study only quantified the overall environmental inputs and outputs and finally obtained a CCEP environmental performance result, which did not involve the impact allocation of each production process. Burchart-Korol et al. (2016) developed a new LCA calculation model and carried out a detailed analysis of coal production in Poland. Their model can be used to assess greenhouse gas emissions within 20, 100, or 500 years, as well as the impact of mining activities on human health, ecosystems, and natural resources. Owing to the differences in geographical area, mining method, and configuration technology, the suitability of the model for the environmental assessment of coal production in China has not been confirmed.

In summary, a comprehensive LCA study on the environmental impacts of coal mining in China is still lacking. Therefore, this study aims to (1) analyse the environmental burden of a typical underground coal mine in China using the LCA method; (2) obtain quantitative results of life cycle impact assessment (LCIA), including uncertainty information; and determine the key impact categories on the environment; (3) identify the key processes that cause environmental pollution through contribution analysis; and (4) perform a sensitivity analysis between the key processes and key impact categories to examine the variation degree of the LCIA results. This study performs an in-depth analysis of the environmental impacts of underground coal mining in China. Some technical measures are proposed based on the LCA results to realise clean and efficient coal production and build a green and sustainable energy system.

2. Materials and methods

2.1. Case study

A typical coal mine in East China was selected as the on-site data source, and the environmental impact related to the coal production life cycle was studied.

The mine adopts the shaft mining mode, and its coal reserve is approximately 573.18 Mt. A comprehensive mechanised coal mining method with a production capacity of 5.00 Mt./a and gangue rate of 15% is adopted. It is estimated that the absolute gas emission is approximately 102.66 m^3/min. Supplies are purchased from a neighbouring city, which is approximately 34 km away, and transported to it. In response to the national call for energy conservation, emission reduction, and green development, the gas drainage method has been replaced by gas extraction in recent years, and gas has been exploited as a resource. The extraction rate is 30% and the annual extraction capacity is approximately 40 million m^3 of which approximately 18 million m^3 is available. In addition, the gas utilisation project was successfully registered in the United Nations Clean Development Mechanism Executive Council in 2007.

In China, more than 95% of the coal is obtained by shaft mining, and approximately 50% of the mines contain large amounts of gas. As one of the typical coal production bases, this mine has benefitted both the environment and economy and set a good example for coal enterprises to develop a circular economy. Therefore, studying the life cycle of this mine is illustrative and has certain guiding significance for the green mining of coal resources.

2.2. LCA of coal production

2.2.1. LCA method

The LCA software SimaPro 9.0.0 was used for analysis in this study. SimaPro is a powerful and reliable LCA software, which can be directly linked to well-known internationally recognised databases such as the Ecoinvent database and Input-Output database. These databases can provide abundant background data resources, including a large number of mining industry datasets, so the software is widely used in the LCIA of the mining industry (Farjana et al., 2019).

In SimaPro, the ReCiPe Midpoint (H) method is used for quantitative calculations. The ReCiPe Midpoint (H) is a problem-oriented method that can reflect the direct impact of the life cycle on the environment. It quantifies the results into 18 impact categories, namely, climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidation formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion. When the coal production life cycle inventory (LCI) is assigned to these impact categories, characterisation analysis can reflect the relative contribution of each process to the impact categories. Normalised analysis can quantify the relative magnitude of each impact category in the overall environmental impact during the life cycle. Thus, the environmental impact of coal production can be clearly determined.

2.2.2. Functional unit and system boundary

The selection of functional unit can provide a quantitative reference for the inputs and outputs of the life cycle to compare and analyse the results of the LCA (ISO 14040, 2006). In this study, 1 t of product coal was selected as the functional unit to assess the environmental burden caused by coal production.

Product systems are often interconnected in a complex manner. It is very difficult to track all the inputs and outputs of a product system; therefore, the boundary of the system must be defined. In this study, the final consumption stage was not considered. The ‘cradle to gate’ path was adopted to assess the life cycle impact.

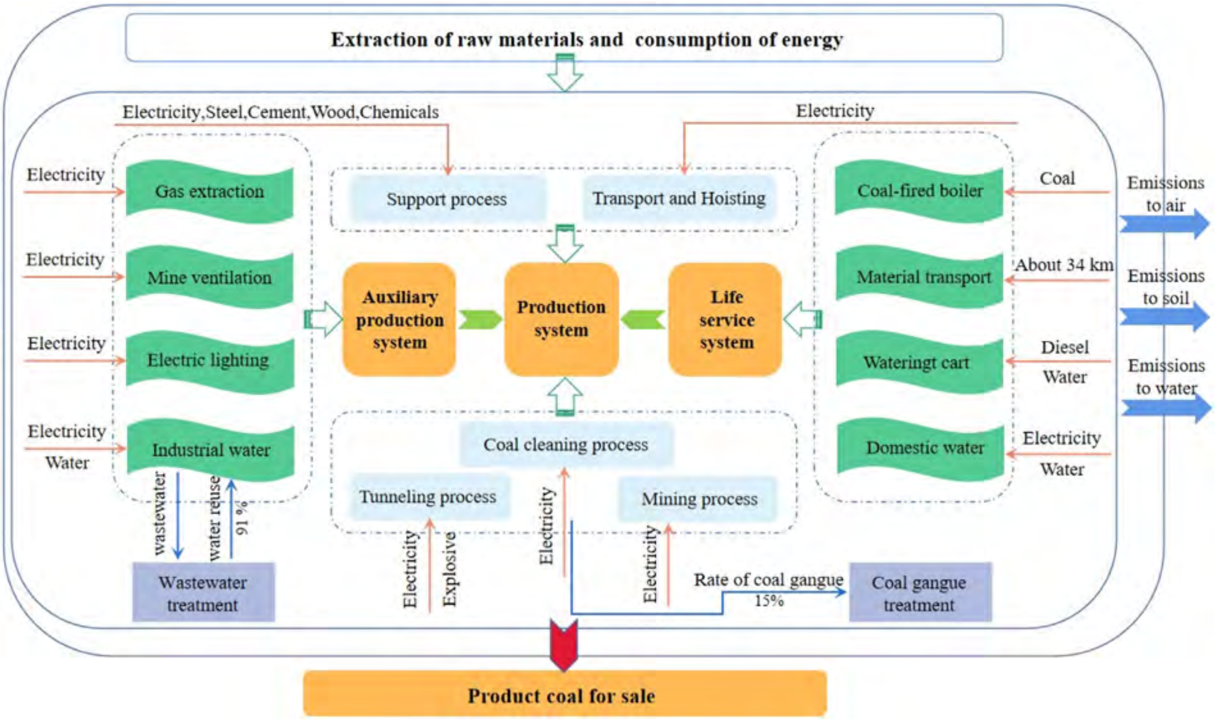

Fig. 1. System boundary of the coal production life cycle.

The system boundary is illustrated in Fig. 1. The LCA from 'cradle to gate' covers three interacting subsystems. It should be noted that the system includes raw material extraction, energy consumption, and the related inputs and outputs of the technological processes for coal production, but not the production and maintenance of mining equipment.

2.2.3. LCI analysis

Data collection is often considered as the preparation phase of the LCI. To obtain the field data, the production parameters and pollution emissions of the coal production processes were monitored. In the case of insufficient data, the government planning data and relevant literature materials were referred to for supplementation. In addition, the most widely used Ecoinvent $_V$3 database was used to provide background data, which was composed of more than 10,000 interrelated datasets, including LCI data of different sectors such as energy production, transportation, building materials, chemical production, and metal production in China and other countries (Ecoinvent Centre, 2018).

Table 1 presents the LCI, which comprises the inputs and outputs in the processes of the life cycle. All procedures, such as material extraction, energy consumption, direct discharge, and waste treatment, were based on functional unit.

Owing to the errors of on-site monitoring data and inevitable data gap, there must be some uncertainties in the data, which can be expressed as a range or standard deviation. To quantify the uncertainties, it was assumed that the measurement data have a logarithmic normal distribution in the LCA, and the lognormal distribution is described by a standard deviation. A typical characteristic of a lognormal distribution is that the square of the geometric standard deviation (GSD^2) covers a 95% confidence interval. The 95% confidence interval range can be obtained by multiplying and dividing the measured values by GSD^2. It can be expressed as

$$Probability\left\{\frac{m}{GSD^2} < X < GSD^2 \bullet m\right\} = 0.95 \tag{1}$$

where m is the measured value of inputs and outputs.

GSD^2 can be calculated based on the pedigree matrix originally developed by Weidema and Wesnæs (1996). It is determined by five uncertainty factors and one basic uncertainty factor. The calculation formula can be expressed as follows:

$$GSD^2_{95} = \exp\sqrt{[\ln(U_1)]^2 + [\ln(U_2)]^2 + [\ln(U_3)]^2 + [\ln(U_4)]^2 + [\ln(U_5)]^2 + [\ln(U_b)]^2} \tag{2}$$

Table 1
Life cycle inventory (Values were presented per functional unit).

	Substance	Unit	Amount	GSD^2
Raw materials	Coal	t	1.00	1.08
	Steel	kg	1.30	1.32
	Cement	kg	5.65	1.32
	Wood	kg	0.56	1.32
	Explosive	kg	4.36E-02	1.26
	Water	m^3	0.29	1.16
	Other chemicals	kg	0.14	1.13
Energy consumption	Electricity	kWh	33.07	1.25
	Diesel	MJ	6.93E-02	1.25
Emissions to air	Methane	kg	18.48	1.41
	Carbon dioxide	kg	44.35	1.34
	Carbon monoxide	g	73.92	1.65
	Hydrogen dioxide	g	22.18	1.65
	Sulfur dioxide	g	31.46	1.65
	Nitrogen dioxide	g	12.24	1.65
	Ammonia	g	66.52	1.65
	Particulates,<2.5 μm	g	8.14	3.12
	Particulates,<10 μm	g	16.71	2.12
Emissions to water	COD,Chemical Oxygen Demand	g	5.87	1.52
	Ammonia, as N	g	0.42	1.52
Emissions to soil	Lead	mg	5.58E-02	1.63
	Chromium	mg	2.07E-02	1.63
	Arsenic	mg	0.25	1.39
	Cadmium	mg	9.00E-03	1.63
	Mercury	mg	7.20E-03	1.63
Waste treatment	Water	t	0.35	1.16
	Coal gangue	t	0.15	1.24
Transportation	Lorry	t·km	1.16	2.25

In the formula, U_1–U_5 stand for the five uncertainty factors of reliability, integrity, time correlation, regional correlation, and further technical relationship. U_b represents the basic uncertainty factor, which is based on judgement by the experts. They can all obtain corresponding scores from the pedigree matrix according to the data source and type. Following the calculation method above, the uncertainties of the input and output data of this study are listed in Table 1.

3. Results

3.1. LCIA results

The environmental relevance of all inputs and outputs can be directly reflected in the LCIA. Coal mining can damage human health, ecosystems, and resources. As previously mentioned, the environmental impact results are divided into 18 categories, such as climate change, ozone depletion, and terrestrial acidification, in the ReCiPe Midpoint (H) method. The parameters of material extraction, energy consumption, and environmental emissions contained in the LCI are automatically assigned to these impact categories in the software to obtain the LCIA results, including the characterised and normalised midpoint results.

3.1.1. Characterised midpoint results

In the characterised midpoint results, all impact categories are scaled to 100% to clearly and intuitively observe the impact of the processes on the individual impact categories. However, it is not easy to determine which process or impact category has the most dominant overall environmental influence. Fig. 2 shows the characterised impact contributions of the three interacting subsystems in the coal production processes.

It can be seen from the figure that the production system plays a very dominant role in the 12 impact categories of ozone depletion, freshwater eutrophication, human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, urban land occupation, natural land transformation, metal depletion, and fossil depletion. The auxiliary production system has a significant impact on climate change, terrestrial acidification, marine eutrophication, photochemical oxidation formation, and particulate matter formation. In particular, it has a contribution rate of 92.4% to the impact category of climate change. In the category of water depletion, the contribution of the life service system accounted for as high as 58.3%, while the production system only accounted for 31.8%. This is due to the reuse of mine water after treatment and the direct discharge of domestic water.

Table 2
LCIA midpoint results (Values were presented per functional unit).

Impact category	Unit	Amount	GSD^2
Climate change	kg CO_2 eq	499	1.20
Ozone depletion	kg CFC-11 eq	7.27E-7	1.32
Terrestrial acidification	kg SO_2 eq	0.377	1.28
Freshwater eutrophication	kg P eq	0.00892	1.22
Marine eutrophication	kg N eq	0.0145	1.28
Human toxicity	kg 1,4-DB eq	10.1	1.25
Photochemical oxidant formation	kg NMVOC	0.357	1.23
Particulate matter formation	kg PM_{10} eq	0.162	1.21
Terrestrial ecotoxicity	kg 1,4-DB eq	0.00198	1.30
Freshwater ecotoxicity	kg 1,4-DB eq	0.663	1.40
Marine ecotoxicity	kg 1,4-DB eq	0.671	1.41
Ionising radiation	kBq U235 eq	0.597	1.39
Agricultural land occupation	m^2a	2.53	1.41
Urban land occupation	m^2a	0.762	1.18
Natural land transformation	m^2	0.00251	1.22
Water depletion	m^3	0.45	1.11
Metal depletion	kg Fe eq	11.9	1.54
Fossil depletion	kg oil eq	443	1.08

In the LCA, the input and output substances are classified according to their chemical properties. A certain typical substance is used as a reference in each impact category, and then specific impact factors are given to other substances to quantify the impact degree. For example, in the climate change impact category, CO_2 is selected as the reference gas. The impact factor of CH_4 is 25 times that of CO_2, so the impact of 1 kg CH_4 on climate change is measured by 25 kg CO_2 eq. Similarly, CCl_3F (CFC-11) is taken as a reference for the ozone depletion category; hence, the result is measured by kg CFC-11 eq.

Table 2 presents the midpoint results of the LCIA, where the potential influence of each impact category can be observed. For example,

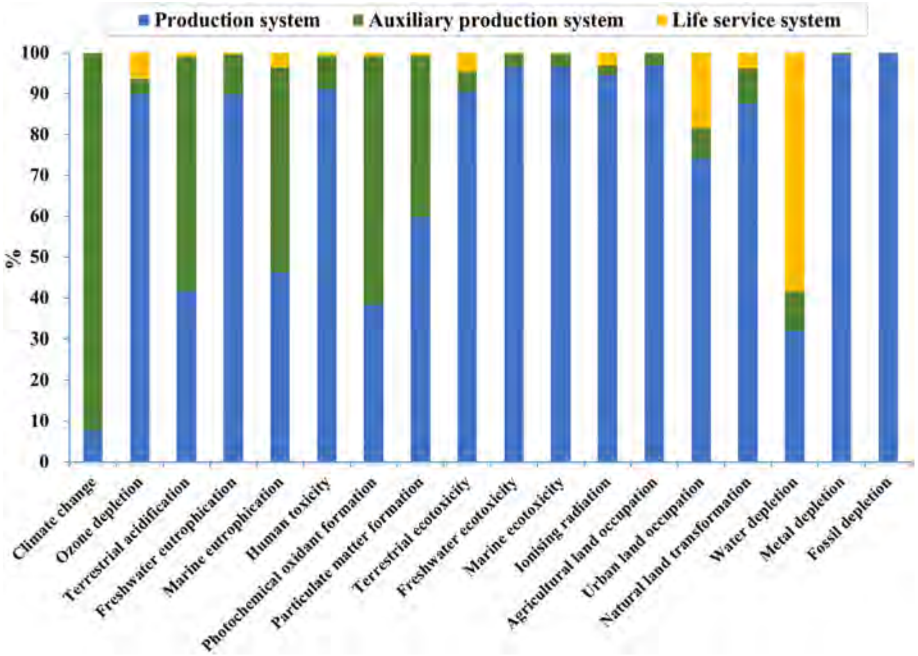

Fig. 2. Characterised results of LCIA.

the impact value of climate change is 499 kg CO_2 eq, ozone depletion is 7.27E-7 kg CFC-11 eq, and terrestrial acidification is 0.377 kg SO_2 eq.

In view of the uncertainty of the input and output data, this study carried out an uncertainty analysis based on the Monte Carlo method to calculate the uncertainty of the LCIA results and improve the reliability of the results. In the Monte Carlo analysis, the number of runs was set to 1000, and the confidence interval was set to 95%. For each dataset, the computer randomly selects a set of data to combine in the confirmed uncertain interval and calculates the results. By repeating the operation 1000 times, an uncertainty distribution can be obtained. It is also expressed by GSD^2, and the uncertainties of each impact category are presented in Table 2. The variation range of the LCIA results can be obtained by multiplying and dividing by GSD^2. For example, within the 95% confidence interval, the impact range of climate change is 415.83 to 598.80 kg CO_2 eq, ozone depletion is 5.51E-7 to 9.60E-7 kg CFC-11 eq, and terrestrial acidification is 0.295 to 0.483 kg SO_2 eq.

3.1.2. Normalised midpoint results

Because the characterisation analysis cannot directly indicate the degree of influence of each impact category on the overall environmental impact, a normalised analysis was carried out. This analysis can be used to quantify the contribution of the different impact categories to the overall environmental impact, as displayed in Fig. 3.

It can be observed that the greatest environmental burden is caused by fossil depletion in the coal mining process. In addition, marine ecotoxicity, freshwater ecotoxicity, climate change, freshwater eutrophication, and human toxicity have significant impacts, while the other impacts are relatively small.

3.2. Contribution analysis

Contribution analysis is an important tool for understanding the uncertainty of the results. Through this analysis, the processes that play an important role in the results can be identified, and then, these processes can be focused on to reduce the damage to the environment. In the contribution analysis results, all contributions from a single process were superimposed.

3.2.1. Group contribution analysis

The group contribution analysis can quantify the contribution of each link of coal production to the impact categories and identify the direction for cleaner coal production. The processes within the system boundary were divided into six groups: mining activities, material consumption, chemical consumption, energy consumption, waste treatment, and others. Fig. 4 depicts the effects of the six groups on the 18 impact categories. Coal mining activities have significant contributions to climate change, terrestrial acidification, marine eutrophication, photochemical oxidation formation, and fossil depletion. In particular, they have a contribution rate of 91.5% to climate change and 98% to fossil depletion. In addition, the environmental impact caused by material consumption is significant and has a large impact on a variety of impact categories, including metal depletion (98.3%), agricultural land occupation (80.5%), ionising radiation (78.6%), marine ecotoxicity, freshwater ecotoxicity, terrestrial ecotoxicity, and ozone depletion. Among the categories of freshwater eutrophication, human toxicity, particulate matter formation, urban land occupation, and natural land transformation, energy consumption is the most important. Compared with other groups, the chemical consumption group has little effect. Others mainly include the transportation of materials and use of domestic water. Except for water depletion (58.3%) and urban land occupation, the other effects are insignificant.

3.2.2. Process contribution analysis

According to the normalised midpoint results indicated in Fig. 3, it can be concluded that the key impact categories are fossil depletion, marine ecotoxicity, freshwater ecotoxicity, climate change, freshwater eutrophication, and human toxicity. To further identify the factors that contribute to the key impact categories, a process contribution analysis was carried out.

Fig. 5 displays the process contribution results. It is shown that the coal mining process is the main cause of fossil depletion, accounting for 98.02%, which is due to the extraction of raw materials from natural resources. The use of supporting material steel is the main cause of marine ecotoxicity and freshwater ecotoxicity, accounting for 76.18% and 75.21%, respectively, and the consumption of electricity has also

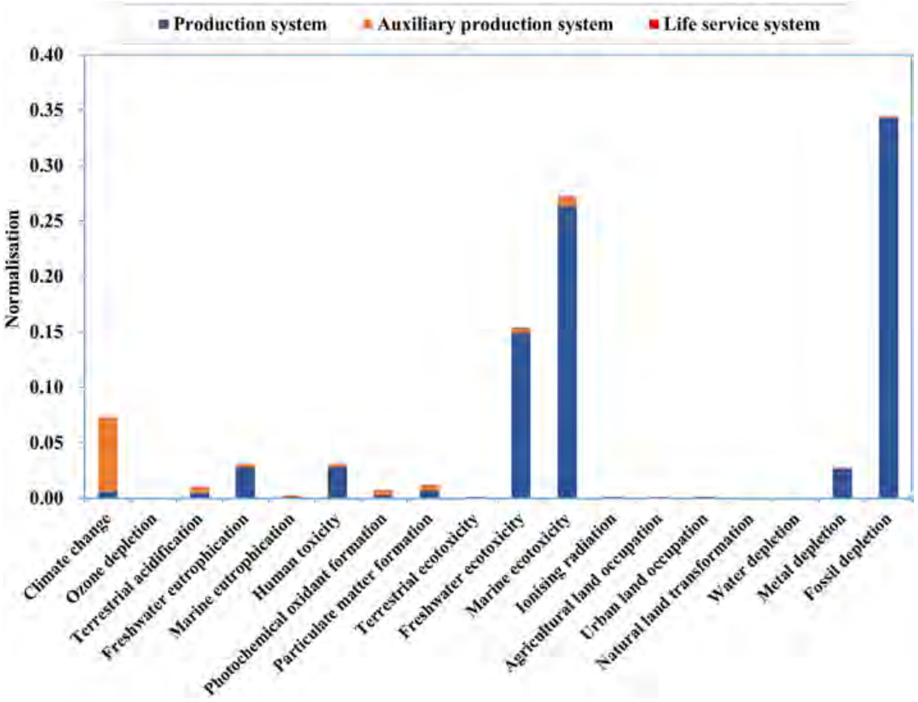

Fig. 3. Normalised results of LCIA.

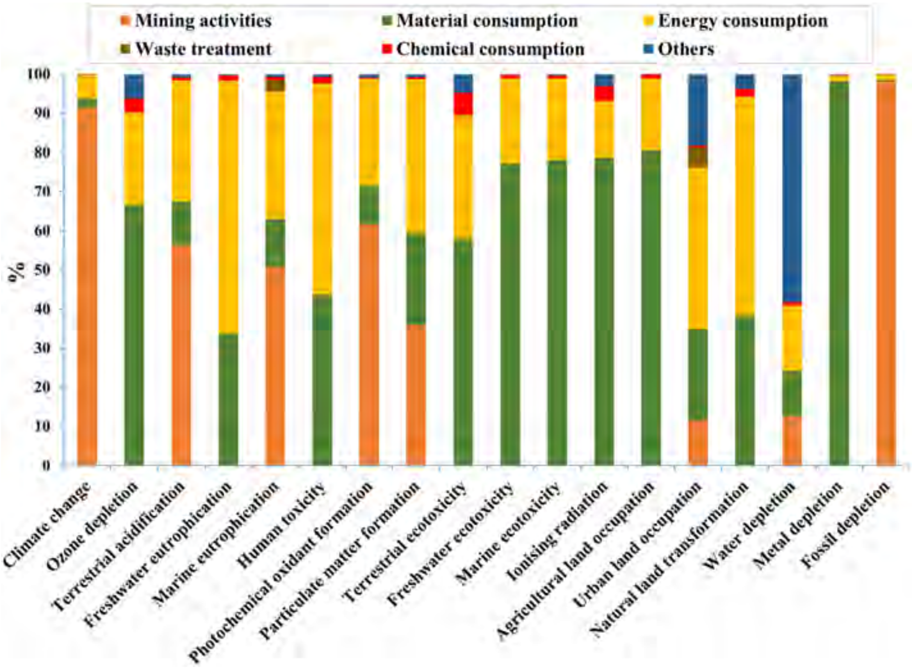

Fig. 4. Group contribution analysis results.

some contribution. Climate change is a global issue. Among the influencing factors of climate change, ventilation is the dominant one, accounting for 91.74%. The effects of freshwater eutrophication and human toxicity are mainly caused by the consumption of electricity, steel, and cement.

From the analysis above, it can be considered that coal mining, electricity consumption, mine ventilation, and the use of steel are the most critical processes causing environmental burden. As a non-renewable resource, the coal mining process has an inevitable impact on the depletion of fossil resources. In recent years, the development of clean and efficient energy sources, such as wind, solar, and nuclear energy, has been vigorously advocated.

3.3. Sensitivity analysis

Sensitivity analysis can provide a basis for scientific decision-making. A sensitivity analysis was conducted on the key impact categories and key processes. Based on the functional unit, the input data of each key process were reduced by 5%, and the contribution changes to the key impact categories were observed. Fig. 6 indicates the results of the analysis. It can be observed that reducing raw coal mining by 5% can provide great environmental benefits to freshwater eutrophication, human toxicity, freshwater ecotoxicity, marine ecotoxicity, and fossil depletion. When mine ventilation is reduced by 5%, the change rates of the climate change and human ecotoxicity categories are 4.61% and 3.22%, respectively, and the impacts on the other categories are small. The change in electricity consumption has the greatest impact on freshwater eutrophication and human toxicity, while the change in steel consumption has a significant impact on freshwater ecotoxicity and marine ecotoxicity.

According to the results of the sensitivity analysis, to reduce the impact on the environment, the first countermeasure is to minimise the development of coal resources, improve the mining and utilisation efficiency, and develop clean energy. Then, in the process of mining the coal resources, it is necessary to increase the utilisation efficiency of electricity and steel. In addition, the gas discharged from the ventilation process has to be recycled or discharged after treatment to considerably reduce its impact on the climate.

4. Discussion

With the rapid development of economic globalisation, environmental issues have become increasingly serious and have been one of the hottest topics worldwide. China's coal-based energy consumption structure has caused large amounts of pollutant emissions. Owing to the excessive dependence on coal resources, accompanied by the lack of technology and management in the production processes, it has caused serious damage to the environment. Exploring the coal production life cycle can accurately capture the environmental factors of coal production and show the direction towards green mining.

In this study, the contributions of the production system, auxiliary production system, life service system, and their unit processes to 18 environmental impact categories were analysed. The LCIA results show that in terms of contribution to the impact categories, coal production and metal production have similar impacts on the environment (Chen et al., 2018). Through the process contribution analysis, the key processes of coal production were identified. These key processes are considered to be the main causes of environmental damage, and they are also objects that need to be focused on in the future. The sensitivity analysis showed the degree of influence of the key processes on the key categories, which provided the basis for scientific decision-making in the control of key processes. The author believes that in order to promote the construction of green mines, it is necessary to strengthen the application of innovative technology in mines and realise the efficient utilisation of resources, modernisation of the mining mode, standardization of mine management, and ecologicalisation of the mining environment.

The concentration of methane emitted by mine ventilation is low, generally in the range of 0.1–1%, which is not only difficult to use, but also causes huge emissions, accounting for approximately 70% of methane emissions from coal (Karakurt et al., 2011). Low-concentration methane can be captured by oxidation methods and used as an auxiliary fuel. There are many oxidation methods, such as thermal flow reversal reactor technology, catalytic flow reversal reactor technology, and catalytic monolithic reactor technology (Gosiewski et al., 2015). Although some progress has been made in low-concentration gas treatment technology, it has not been well promoted and applied. In most cases in

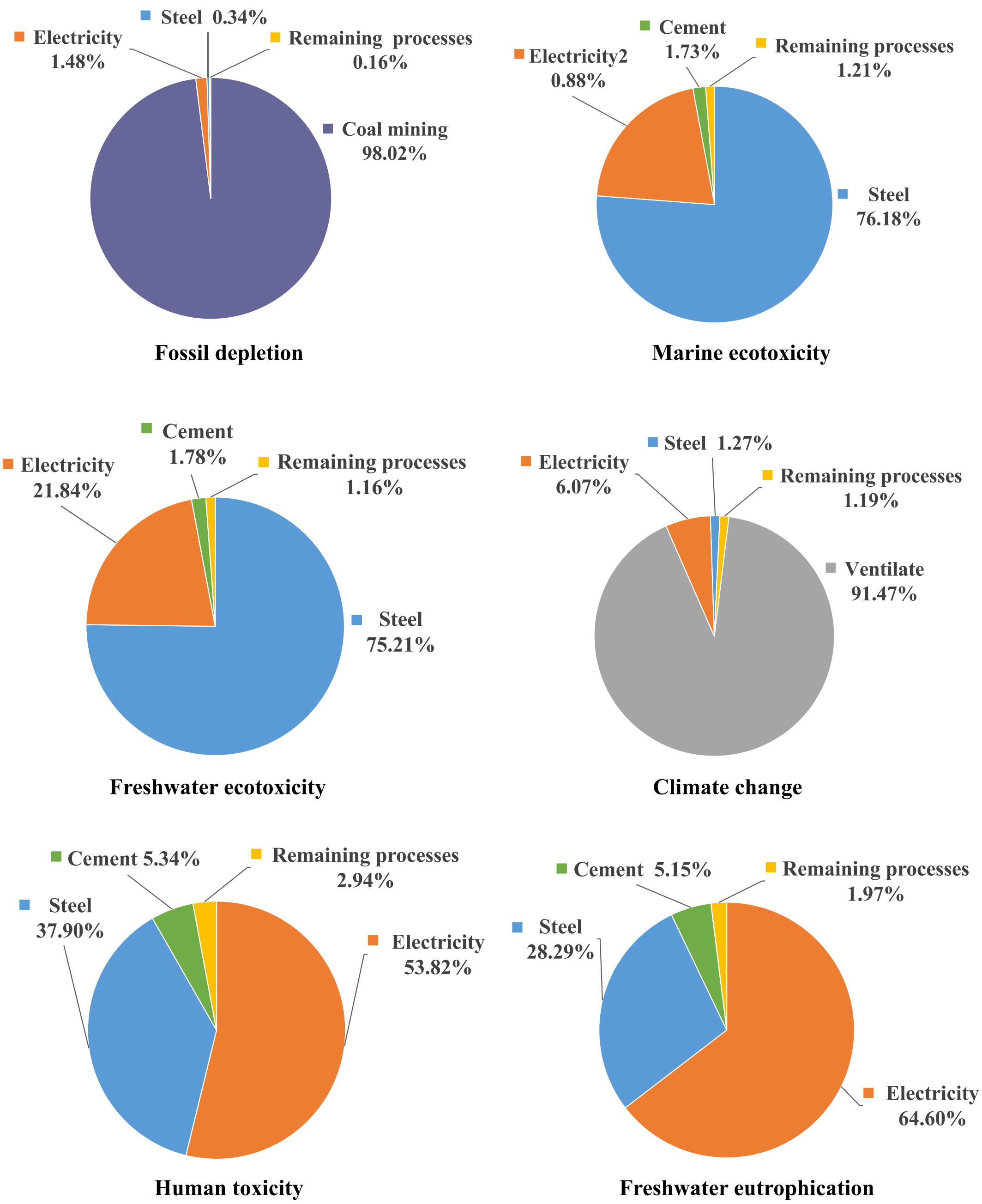

Fig. 5. Process contribution analysis results.

China, low-concentration methane is directly discharged into the atmosphere. The global warming potential of methane is 25 times that of carbon dioxide, and direct emissions will impose a heavy burden on the environment. To save energy and reduce emissions, the state should strengthen technology research, develop ventilation gas utilisation technologies, and recycle ventilation gas according to the actual situation of coal enterprises in China.

Compared with the ventilation process, gas extraction can not only ensure the safety of coal production but also provide some economic and environmental benefits. The greater the amount of gas extracted, the less the quantity discharged by the ventilation. The gas extraction technology in China has been relatively mature, but it is also encountering some problems, such as low utilisation rate, poor permeability of coal seams, and difficulty in drilling soft coal seams, which limit the development of coal-bed methane (Wang et al., 2014). Some scholars have conducted in-depth research in this area. Yan et al. (2015) proposed a method of combining hydraulic fracturing and hydraulic slotting to improve the mining efficiency of high-permeability and low-concentration coal-bed methane. Xia et al. (2014) studied a new hole-sealing technology that used small expansion particles to seal the leakage cracks around the pipeline and improve the gas extraction concentration. The continuous renewal and application of coal mine gas extraction technologies have promoted the comprehensive utilisation of coal resources and reduced the emission of greenhouse gases to a certain extent.

As the study case is a high-gas mine, the gas drainage method was adopted to ensure safe mining in the early period, and the extracted gas was discharged directly into the atmosphere, posing a significant threat to the environment. In the later reconstruction process, the gas drainage was replaced by gas extraction. Of the available gas extracted, approximately 15 million m^3 is used for power generation and 3 million m^3 is supplied for civil use every year. The impacts of the two modes on

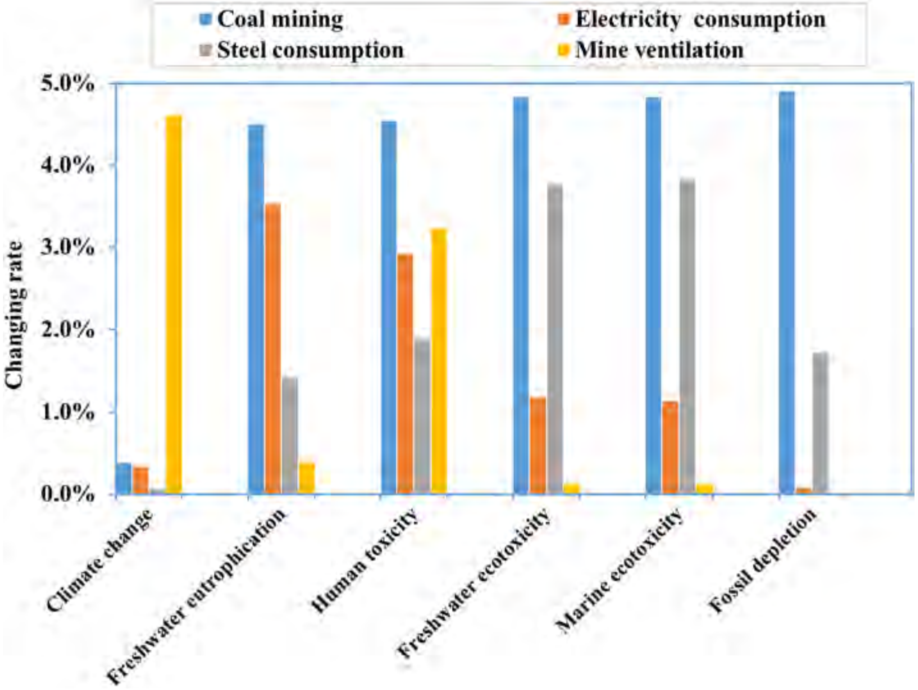

Fig. 6. Sensitivity analysis results of key processes.

the key categories were compared. The results are presented in Table 3. It is evident that compared with the gas drainage mode, the gas extraction mode can reduce the environmental burden, particularly providing approximately 24% environmental benefit in terms of climate change.

The most direct way of reducing the impact of electricity and steel consumption on the environment is to improve the utilisation efficiency and recycle waste steel (Ma et al., 2018). The environmental burden of electricity is caused by power generation, and 48% of the coal consumption in China is used by the power generation industry (Restrepo et al., 2015; Zhao et al., 2019). Yu et al. (2014) studied the carbon emissions of China's coal power energy chain and found that the greenhouse gases from coal combustion accounted for 93.8% of the total emissions, while the emissions from mining, transportation, and other processes only accounted for 6.2%. Zhao et al. (2015) analysed the environmental and economic burden of six commonly used lignite power generation scenarios and found that two pre-drying technologies, i.e. super steam fluidised bed and superheated steam drum, were more suitable for lignite power generation. Wang et al. (2018) asserted that solar-assisted coal-fired power generation could effectively improve the power generation efficiency. Wilberforce et al. (2019) proposed a variety of carbon capture and storage technologies that can effectively reduce greenhouse gases in the process of power generation. Regarding the clean and efficient combustion of coal, carbon capture and storage as an important direction, meets the requirements of green and low-carbon development.

The alternative use of solar energy, wind energy, nuclear energy, and other clean energy sources can avoid pollution at the origin. In recent years, the research on new energy has developed rapidly worldwide. The three fields of solar energy, hydrogen energy, and energy storage have received widespread attention. Solar energy photovoltaic technology, solar energy fuel technology, and battery energy storage technology are considered to be the most promising technologies. At present, the scale of China's renewable energy development and utilisation ranks first in the world. By the end of 2020, the installed capacity of renewable energy power generation in China reached 930 MW, accounting for 42.4% of the total. This is a 14.6% increase compared to that in 2012. The continuous improvement of the renewable energy utilisation level provides strong support for the green and low-carbon transformation of energy (SCIO, 2021).

Reducing carbon emissions to achieve carbon neutrality is a serious global challenge facing the world. In 2019, the global carbon emissions reached 40.1 billion tonnes of carbon dioxide, 86% of which came from fossil combustion (Ding, 2021). At the 75th United Nations General Assembly, China announced that it would strive to reach the peak of carbon emissions by 2030 and achieve carbon neutrality by 2060. As coal is the focus of emission reduction in the context of carbon neutrality, its production capacity reduction and technological breakthroughs require a long period, and more effort is required in this field. To achieve the goals of carbon peak and carbon neutrality as soon as possible, first, it is necessary to strictly control emissions at the source and strengthen regulations to realise the collaborative governance of 'reducing pollution and carbon'. Second, it is necessary to substantially increase the proportion of new energy and renewable energy power

Table 3
Comparison of gas extraction and gas drainage production modes (Values were presented per functional unit).

Impact category	Unit	Gas extraction	Gas drainage	Change rate
Climate change	kg CO_2 eq	499	617	23.65%
Freshwater eutrophication	kg P eq	8.92E-2	9.43E-2	5.72%
Human toxicity	kg 1,4-DB eq	10.1	10.5	3.96%
Freshwater ecotoxicity	kg 1,4-DB eq	0.663	0.676	1.96%
Marine ecotoxicity	kg 1,4-DB eq	0.671	0.683	1.79%
Fossil depletion	kg oil eq	443	443	0

generation, accelerate the process of substituting coal with clean energy sources, reduce the proportion of coal consumption in the industrial sector, and achieve a clean and low-carbon energy transition.

Owing to the limitation in production data, the research excludes the consumption stage such as coal combustion (the end of the life cycle) from the system boundary. A complete coal life cycle should include the production processes, product distribution, product consumption, etc., but this is a complex and extremely large system. The assessment of the entire life cycle ('cradle to grave') can fully reflect the environmental impact of the coal energy chain, and more research needs to be done in this area.

5. Conclusion

With the development of the social economy, the demand for energy is increasing. China is facing environmental challenges caused by coal mining. To quantify the impact of coal production on the environment, this study used the LCA method to analyse the coal production of a typical mine in China.

The midpoint results of the LCIA with uncertainty information were obtained and normalised. The normalised midpoint results indicate that the most important environmental impact categories are fossil depletion, marine ecotoxicity, freshwater ecotoxicity, climate change, freshwater eutrophication, and human toxicity. The other environmental impacts are relatively small. Then, a contribution analysis was carried out. The results show that mining activities, consumption of steel and electricity, and mine ventilation are the key processes that cause environmental pollution. Among them, mining activities cause huge fossil depletion, with a contribution rate of 98.02% of the entire process. Steel consumption contributes more than 70% to marine ecotoxicity and freshwater ecotoxicity. Freshwater eutrophication and human toxicity are mainly caused by electricity consumption, with contribution rates of 64.60% and 53.82%, respectively. In addition, mine ventilation has a huge impact on the climate, with a contribution rate of 91.47%, which should be taken seriously. Finally, a sensitivity analysis was performed with the input values of the key processes as the independent variables. The results indicate that to solve the environmental problems, priority should be given to reducing coal resource mining and improving the efficiency of coal mining and utilisation. This study also confirms that applying the gas extraction mode can not only ensure mining safety and increase the economic benefits but also provide approximately 24% environmental benefits to the climate.

Based on the analysis results above, to promote the sustainable development of the green coal industry and achieve the goal of carbon peak and carbon neutrality as soon as possible, the state needs to actively promote energy transformation and accelerate the development of renewable energy. In view of the existing coal production, it is necessary to vigorously promote technological innovation, strengthen the reuse of recyclable resources such as ventilation gas and extracted gas, and strictly control pollution emissions. In addition, improving the utilisation efficiency of product coal is an important means for realising green and clean energy development.

CRediT authorship contribution statement

Ming Tao: Conceptualization, Software, Project administration, Supervision, Writing – review & editing. **Wenqing Cheng:** Investigation, Software, Methodology, Writing – original draft. **Kemi Nie:** Supervision, Software, Methodology. **Xu Zhang:** Software, Methodology, Validation. **Wenzhuo Cao:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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