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Life cycle assessment for waste acid treatment in zinc smelting

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Abstract: Lift cycle assessment (LCA) methodology was applied to evaluating and comparing two waste acid disposal processes in zinc smelting. The results indicate that environmental impacts of gas−liquid vulcanization technologies are human toxicity, abiotic depletion potential, and global warming risk, which are mainly caused in neutralizing−evaporating−crystallization unit and electrodialysis unit. As for traditional lime neutralization method, vulcanization unit is the main factor. In this regard, the total environmental impact of traditional lime neutralization method is much higher than that of gas−liquid vulcanization technologies. Furthermore, the sensitive analysis shows that electricity and sodium sulfide (60%) are sensitive factors in two waste acid disposal technologies. In addition, the total cost of disposing a functional unit waste acid in traditional lime neutralization process is nearly 27 times that of the gas−liquid vulcanization waste acid disposal technologies.

Key words: zinc smelting; waste acid treatment; life cycle assessment; environmental impact

1 Introduction

High concentration sulfur-containing flue gas is produced in lead−zinc smelting process as lead and zinc mostly exist in sulfur concentrate in the form of sulphur compounds [1,2]. The sulfur-containing fume is usually purified with 5% dilute sulfuric acid to remove pollutants such as lead, zinc, fluorine and chlorine, so as to improve the quality of sulfuric acid products. In the above flue gas purification process, a large amount of acid wastewater (waste acid for short) are produced [3,4]. Without effective disposal or direct discharge, it will not only cause serious environmental pollution, but also lose valuable metals and sulfur resource [2,5,6]. The treatment methods of these waste acids include chemical precipitation, adsorption method, ion exchange method, membrane separation method and extraction method [7−11], etc. However, there are some problems with those traditional methods in the practical application. Extraction method has a high operating costs and a few practical demonstrations in domestic industrial [7,10], separation efficiency of the membrane separation method is dissatisfied at room temperature and the separation efficiency is particularly vulnerable to the properties of the separation membrane [10−12]. At present, domestic and foreign sewage acid wastewater treatment technologies are mainly chemical precipitation and sulfide methods. Lime neutralization method as a

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traditional chemical precipitation disposal method is widely used in lead−zinc smelting enterprises, which increases a large number of waste slag with heavy metals and neutralization slag with calcium and fluorine ions, leading to severe environmental problems and increasing the follow-up cost of disposing solid wastes [12−14]. In addition, these waste residues containing heavy metals such as lead, cadmium and mercury obtained from traditional lime neutralization treatment are labelled as hazardous wastes on the basis of national regulations, which should comply with relevant laws and standards in stacking, transportation and treatment [15,16]. If above waste residues cannot be effectively handled, the contained heavy metals may percolate out and spread into water or soil, causing serious environmental problems and ecological damages [3,17,18].

In the view of the technical bottlenecks and difficulties in the disposal of waste acid from traditional lime neutralization method in zinc smelting, a new method named gas−liquid vulcanization method was jointly proposed by Central South University and lead−zinc smelting enterprise in nonferrous industry [4,19,20]. Compared with the traditional lime neutralization process, the gas−liquid vulcanization process uses a gas−liquid enhanced vulcanization device to remove arsenic, cadmium and other heavy metals from the waste acid, followed by the selective electrodialysis to concentrate waste acid. After that, the sulfuric acid concentration is increased from 2.95% to about 10%, and then catalytic stripping unit and evaporating−crystallization unit are used to increase acid concentration from about 10% to more than 70%, so as to realize the direct separation of fluorine and chlorine from solution [21,22]. According to the long-term operation practices of sewage acid disposal demonstration projects in several zinc smelting enterprises, this new technology is proven to be able to greatly reduce the generation of hazardous waste residue and effectively solve the environmental problems caused by hazardous waste residue, realizing the recycling of sulfuric acid and increasing the economic benefits of enterprises [19,22].

Life cycle assessment (LCA) is an internationally recognized environmental assessment tool for evaluating a product's environmental burden by quantifying the impacts of all inputs and outputs associated with corresponding production processes (ISO 14040, 2006), which is an important tool for environmental authorities and policymakers to make environmental strategies [23,24]. Currently, LCA has been extensively applied for evaluating the environmental impacts generated from metallurgy industry, such as aluminium, steel, zinc, and lead [25,26]. However, The studies on treatment of waste acid in zinc smelting by LCA has not been reported yet. Consequently, it is necessary to conduct a systematic study for identifying the key processes and main substances generated during waste acid treatment in zinc smelting to reduce the environmental burden and impact on human beings. In this sense, LCA, as a valuable tool, can play an important role in evaluating products and processes from the aspect of their environmental impacts in favour of assisting in decision-making processes [23,25,27,28]. The goal of this study includes the evaluation and comparison of two treatment of waste acid in zinc smelting by virtue of LCA methodology: the traditional lime neutralization method and the gas−liquid vulcanization process.

2 Methodology and data

As defined by the ISO 14040 and ISO 14044, an LCA is structured by four stages, which includes the goal and scope, the life cycle inventory (LCI), the life cycle impact assessment (LCIA), and interpretation [27,29]. This study selects "1000 m^3 waste acid in zinc smelting" as the functional unit to carry out life-cycle environmental impact evaluation. Gas−liquid vulcanization waste acid disposal technologies and traditional lime neutralization methods are concerned specifically. The evaluation is conducted based on the canonical international standards of framework (ISO, 2006a) and process (ISO, 2006b).

2.1 Goal and scope

The goal of this work is to analyse the potential environmental impact of the traditional lime neutralization method and gas−liquid vulcanization waste acid disposal technologies in zinc smelting, thus comparing their impacts under several impact categories. The scope of this work is the environmental emissions.

In this study, 1000 m^3 waste acid in zinc smelting was chosen as the functional unit. System boundary is shown in Fig. 1, in which the processes of raw materials and energy production, waste disposal, transport, and direct emissions of all stages of waste acid disposal process were included. All raw materials, pollutants emission and energy consumption were based on this research functional unit. The system boundary for both technologies covered the major production process, including gas−liquid reinforcement unit (hydrogen sulfide gas generating, gas−liquid enhanced vulcanization reacting and waste acid sedimentation treatment), electrodialysis unit (selective electrodialysis and evaporative concentration), catalytic stripping unit, neutralizing−evaporating−crystallization unit (neutralizating, evaporation and crystallization), vulcanization unit, and evaporating−crystallization unit, as shown in Fig. 1. The assumptions were as follows. Waste acid in zinc smelting from different technologies has the same quality. The environmental impacts from the plant construction are also not included in this analysis. The impacts of upstream production, such as electricity, natural gas, limestone and other raw materials are not considered on the system boundary. In order to simplify the calculation, several complex processes were integrated to one step. For example, two-stage vulcanization included one-stage and two-stage.

2.2 Life cycle inventory and data sources

LCI includes data collection and calculation, which calculates the energy and resource consumption of each unit and the emission amount of various pollutants in the whole research processes, and then make a summary calculation of the data [29,30].

In this study, resources, energy consumption and pollution data of treating waste acid were collected mainly from the survey of typical enterprises and there are two types of data used: foreground data and background data. The former refer to the materials and energy that are directly input into the production process, and the latter refer to the resource consumption and the environmental impacts of these materials and energy in their respective manufacturing processes. The foreground data used in this work are dominated data and were provided by the relevant typical zinc smelting enterprises, including all the raw material input data for evaporating−crystallization, catalytic stripping, electrolysis, etc, and other processes and the corresponding data with economic value. The background data on the environmental impacts of various feedstocks and emissions have been obtained from the GaBi database, which is chosen for comparison due to its popularity in the LCA community [30−32].

Table 1 presents the life cycle inventory of treating 1000 m^3 waste acid in zinc smelting process. The on-site data (e.g., raw materials, energy consumption and direct emissions to environment) in Table 1 were mainly obtained from the survey of waste acid disposal technology and typical zinc smelting enterprises in this study. The background data on treating waste acid in zinc smelting process for each raw material, solid waste, and energy production were obtained from GaBi (ts vision) and Ecoinvent database.

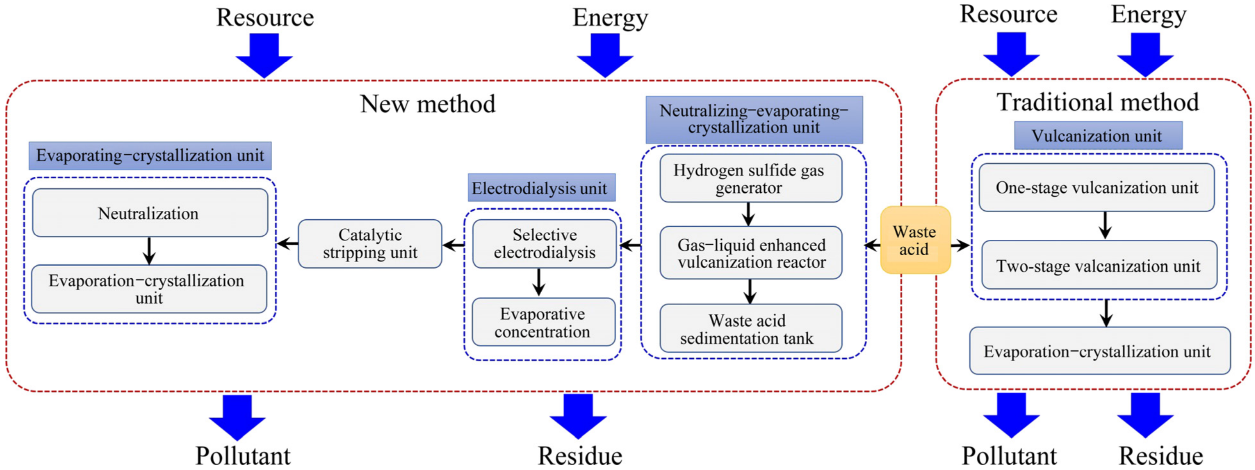

Fig. 1 System boundary of two strategies for waste acid treatment in zinc smelting

Table 1 Life cycle inventory of treating 1000 m^3 waste acid in zinc smelting process (values were presented per functional unit)

Item	Input and output	Gas−liquid vulcanization waste acid disposal technology	Traditional lime neutralization method
Resource and energy consumption	Waste acid/m^3	1000	1000
	Sulphuric acid (30%)/kg	9.91	−
	Sodium hydrosulfide (70%)/kg	17.05	−
	Sulphuric acid (98%)/kg	153.79	−
	Sodium carbonate/kg	26.52	−
	Sodium sulfide (60%)/kg	−	23580.81
	Sodium hydroxide (100%)/kg	−	1318.18
	Limestone/kg	−	104843.43
	Fresh water/m^3	−	360.00
	Electricity/(kW·h)	435	203
Production and waste	Sodium sulfide/kg	23.86	−
	Calcium fluoride (water content 20%)/kg	8.08	−
	Calcium chloride (water content 20%)/kg	17.99	−
	Sulfur slag (water content 50%)/kg	20.83	25631.31
	Sulphuric acid (98%)/kg	153.79	−
	Blow off slag/kg	6.76	−
	Neutralization slag/kg	−	188207.07
	Carbon dioxide/kg	−	46089.63
	Exhaust/m^3	2.13	103.78

2.3 Life cycle environmental impact (LCAI)

LCAI is the core step of the LCA, which associates inventory data with specific environmental impact categories as well as category indicators and transforms into a potential of consumption on the resource, human health effects, ecological impacts, and other environmental impacts [31]. Combined with the characteristics of non-ferrous industry production in China, the CML2001 method (2016 revision) was selected for environmental impact accounting in this study. The CML2001 method (2016 revision) is a problem-oriented approach proposed by the Netherlands Institute of Environmental Sciences of Leiden University, which focuses on process characterization, also known as the midpoint method [26]. CML 2001 method (2016 revision) divides the environmental impact into 12 types, which has been widely used in the world since the LCA becomes popular. In this study, combined with the characteristics of waste acid in zinc smelting process, the five commonly-used indicators were selected for analysis in this study: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP) and human toxicity potential (HTP).

In this study, the environment impact analysis is conducted by utilising the Gabi software (ts version). Characteristic models of treating waste acid in zinc smelting process include influence type and parameter, characterization, normalization and weighting (CML 2001 method, 2016 version, including biogenic carbon). The common normalized benchmark value nowadays is ordinarily the total emissions or resource consumption within the global, regional or national area. This software is developed by the IKP Institute of the University of Stuttgart, Germany. It is one of the most versatile softwares in the world and has numerous datasets of non-ferrous metal industry, which facilitates to calculate indirect environmental impact and total environmental impact in this research. Through this assessment tool, the results in terms of input environmental emissions and resources utilization can be obtained and analyzed.

3 Results and discussion

3.1 Material and energy balances

The mass and energy balances of both waste acid disposal technologies were studied to further understand the reliability of the life cycle inventory (Fig. 2). For both scenarios, the initial waste acid in zinc smelting mass was 1000 m^3. For gas−liquid vulcanization waste acid disposal technologies, the production masses of sodium sulfide, calcium fluoride (water content 20%), and calcium chloride (water content 20%) were 23.86, 8.08 and 17.99 kg, respectively. Sulfur slag (water content 50%) was the only solid waste in the entire new waste acid disposal technologies and its amount was 20.83 kg. For the traditional lime neutralization method, solid wastes were sulfur slag (water content 40%) and neutralization slag, which weighted 25631.31 and 188207.07 kg, respectively. The amount of solid waste by traditional lime neutralization method is much larger than that of new waste acid disposal technologies.

The energy consumption analysis shows that the electricity consumption of gas−liquid vulcanization waste acid disposal technologies is higher than that in traditional lime neutralization method. Through the above analysis, it can be seen that gas−liquid vulcanization waste acid disposal technologies discharge less solid waste than traditional lime neutralization method, which significantly decreases the cost in subsequent disposal of solid waste, reducing production costs and improving economic benefits.

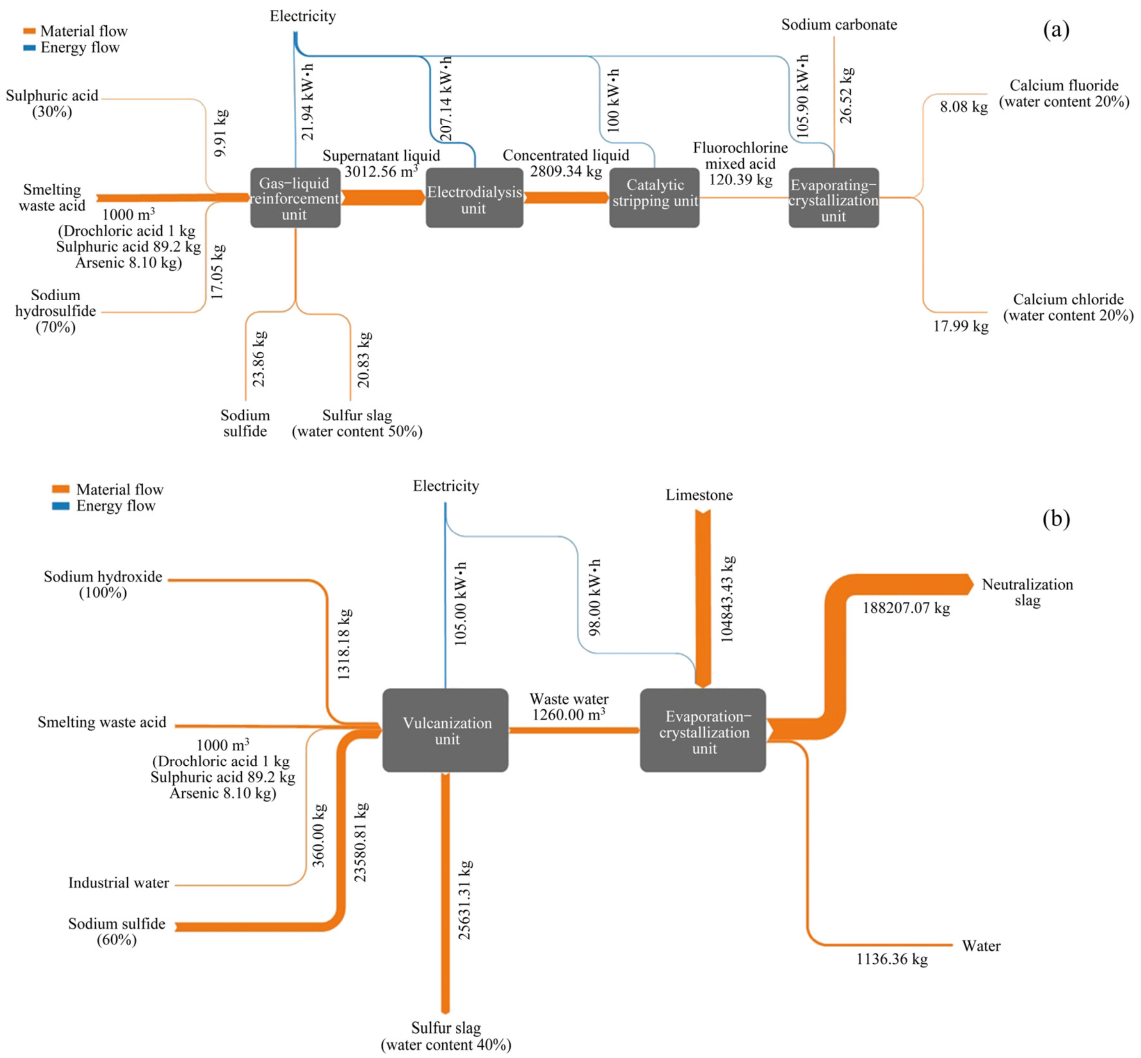

Fig. 2 Mass and energy balances in gas−liquid vulcanization waste acid disposal technologies (a) and traditional lime neutralization method (b)

3.2 Characterization results

Gabi software (ts version), the Netherlands CML 2001 method developed by the Environmental Science Center of Leiden University, and the equivalent factor method were used in this study. In the case of the same quality, the main impact factor of a certain type of environmental impact was taken as a benchmark. And the environmental impact of waste acid treatment in zinc smelting life cycle is characterized by the model Analyze. By this equivalent factor method, we can compare the same amounts of other pollutants with benchmark, and then obtain the each characterization factor according to the equivalent relationship among the various impact factors. Through the calculation of the above influencing factors, the potential environmental impact potential based on benchmark can be obtained.

3.2.1 Gas−liquid vulcanization waste acid disposal technologies

In this study, the potential environmental impacts were generated from all inputs and on-site emissions associated with waste acid treating process in zinc smelting. The characterization result of gas−liquid vulcanization waste acid disposal process is shown in Fig. 3. The human toxicity potential, which generally attracts public’s attention, is also considered. As for GWP, AP, EP, ADP and HTP indicators, the contributions are shown as the order from neutralizing−evaporating−crystallization unit, catalytic stripping unit, electrodialysis unit to gas−liquid reinforcement unit. The impacts from other categories are negligible. The detailed analysis of each indicator is shown as follows.

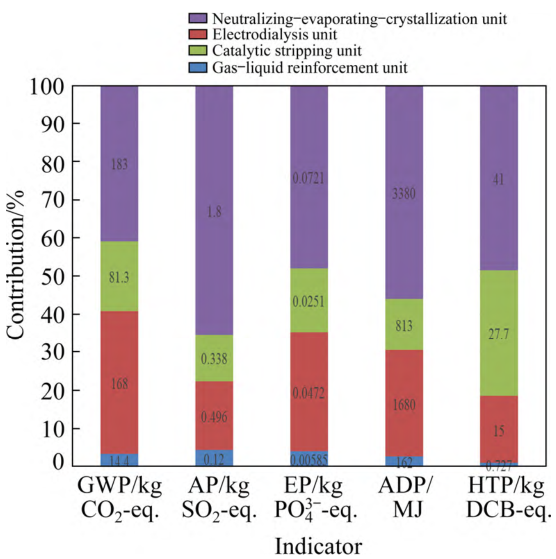

Fig. 3 Characterization result of gas−liquid vulcanization waste acid disposal technologies

For GWP, the characterization value is 446.7 kg CO_2-eq. in total, among which the neutralizing−evaporating−crystallization unit and the catalytic stripping unit occupy majority shares, which are 40.96% and 37.61%, respectively. The CO_2 mainly comes from the usage of energy, while neutralizing−evaporating−crystallization unit and catalytic stripping unit need to obtain higher energy consumption, which mainly comes from coal and part of the system waste heat.

For AP, in total value of 2.75 kg SO_2-eq., the neutralizing−evaporating−crystallization unit, electrodialysis unit and catalytic stripping unit account for 65.36%, 18.01% and 12.27%, respectively. Waste acid mainly contains sulfuric acid, fluorine ions, chloride ions and some heavy metal ions. A large amount of acid mist containing sulfur dioxide can be generated in the neutralization evaporation crystallization process. In addition, a large amount of heat energy is required in the neutralization evaporation crystallization process, which is mainly provided by coal. However, the sulfur compounds in coal can form SO_2 during combustion. The important factor of SO_2 which can effectively increase AP is concentrated during the neutralizing−evaporating−crystallization process, resulting in a higher contribution rate.

For EP, the characterization result is 0.15 kg PO_4^{3-}-eq., which is mainly derived from neutralizing−evaporating−crystallization unit (47.99%) and electrodialysis unit (31.41%). In summary, neutralizing−evaporating−crystallization unit and electrodialysis unit are major contributors in each impact indicator at all stages of the life cycle.

For ADP, the characterization value is 6035 MJ in total. The neutralizing−evaporating−crystallization unit, catalytic stripping unit, and electrodialysis unit account for 56.00%, 27.84%, and 13.47%, respectively. The reason is that the neutralization evaporative crystallization unit needs more energy than other process units. In this study, the energy mainly comes from the hot steam generated in the industrial boiler room and the smelting flue gas collected in the production of the enterprise. Considering that the coal is the mainly fuel in boilers, it is chosen to be a dominated influencing factor of ADP index of new waste acid disposal technologies in zinc smelting.

For HTP, the total amount is 84.43 kg DCB-eq., and the main contribution comes from neutralizing−evaporating−crystallization unit, catalytic stripping unit and electrodialysis unit, with contributions of 48.56%, 32.81% and 17.77%, respectively. Waste acid in zinc smelting contains a certain amount of heavy metals, such as arsenic, and cadmium, which causes severe metal pollution and endanger human health if it is emitted into the air or discharged directly into the water and soil.

3.2.2 Traditional lime neutralization method

The environmental impact of traditional zinc smelting wastewater processes was characterized, and the result is shown in Fig. 4. The GWP of traditional zinc smelting wastewater processes is 34500 kg CO_2-eq., and the contributions of the vulcanization unit and evaporating−crystallization unit are 64.93% and 35.07%, respectively. The emission of CO_2 is the most important factor leading to global warming, which mainly depends on energy use.

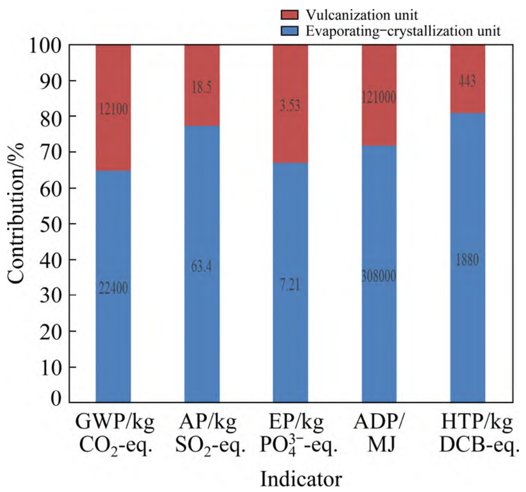

Fig. 4 Characterization result of traditional lime neutralization method

For AP, the characterization result is 81.9 kg SO_2-eq., and the emission of SO_x has an effect on this value. The contributions of the vulcanization unit and evaporating−crystallization unit are 77.41% and 22.59%, respectively. The reason is that sulfuric acid mist is generated in the evaporating− crystallization process, which causes a high AP of the electrorefining process.

For EP, the value is 10.74 kg PO_4^{3-}-eq., with a contribution of 67.13% for the vulcanization process. Ammonium nitrate and ammonia are the main substances that cause eutrophication.

For ADP, the characterization result is 4.29×10^5 MJ during the life cycle. Vulcanization unit and evaporating−crystallization unit are the key processes which account for 71.79% and 28.21% in the total environmental impact, respectively. In terms of the life cycle inventory, these two processes require a larger amount of energy.

For HTP, the characterization result is 2323 kg DCB-eq., among which the vulcanization process contributes 80.93%. Waste acid in zinc smelting has complex components and contains several metals, such as As, Hg and Cr. The HTP of the vulcanization process depends on the removal rate of heavy metals from waste acid during the vulcanization process because the emission of heavy metals is crucial to human toxicity.

3.3 Results of total environmental impact

To further generalize the environment impact, weights are given to each index after the characterization in this study. Then weighting and normalization calculation are carried out and a single value of comprehensive environmental impact is obtained, which is conducive to the comparison of whole environment impacts of both technologies. The normalized reference value and weight in this study are selected with the Gabi software (ts version) of CML 2001 method (2016 version). Weights of each environmental impact indicator are given in Table 2 and corresponding standardized benchmark values are given in Table 3. Gabi software (ts version) is used as the calculation software and the environment impact model was built for both technologies.

According to the calculation and description, normalization and weighting are obtained after characterization. Dimensionless value of different waste acid treatments in zinc smelting is obtained by comparing characterization results of new waste acid disposal technologies and traditional lime

Table 2 Weights of environmental impact indicators

Indicator	Weight
Global warming potential (GWP)	9.3
Abiotic depletion (ADP)	7.0
Acidification potential (AP)	6.1
Eutrophication potential (EP)	6.6
Human toxicity potential (HTP)	7.1

Table 3 Standardized benchmark values of environmental impact indicators

Indicator	Normalized reference value
Global warming potential (GWP)/kg CO_2-eq.	4.22×10^{13}
Abiotic depletion (ADP)/MJ	3.80×10^{14}
Acidification potential (AP)/kg SO_2-eq.	2.39×10^{11}
Eutrophication potential (EP)/kg PO_4^{3-}-eq.	1.58×10^{11}
Human toxicity potential (HTP)/kg DCB-eq.	2.58×10^{12}

neutralization method with the standardization reference values, and then each index is weighted and the total environmental impact is obtained, which is conducive to comparison of whole environment impacts of the traditional lime neutralization method and new waste acid disposal technologies in zinc smelting.

Figure 5 presents the environmental impact values of each waste acid treatment unit in gas−liquid vulcanization waste acid disposal technologies. The total environmental impact of new waste acid process in zinc smelting was 5.19×10^{-10}. The most influential process of waste acid treatment is the neutralizing−evaporating−crystallization unit, which accounts for 51% of the total value approximately, followed by 23.9% of electrodialysis unit, 22.9% of catalytic stripping unit, and 2.21% of gas−liquid reinforcement unit. The largest impact of waste acid treatment on the environment is HTP, which accounts for 44.8%, followed by ADP, GWP and AP, which occupy approximately 21.4%, 19% and 13.6% of the total

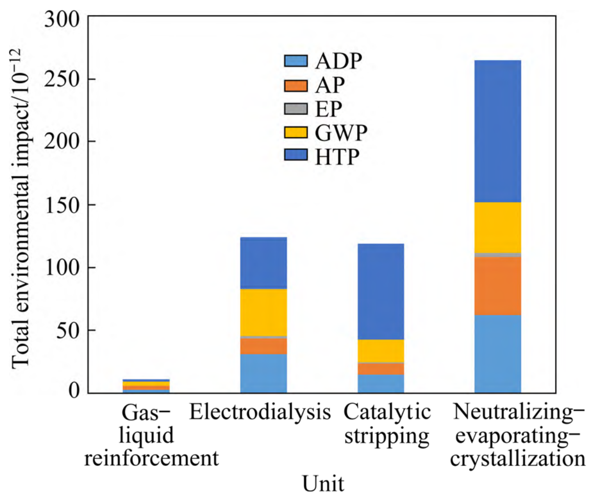

Fig. 5 Total environmental impacts of gas−liquid vulcanization waste acid disposal technologies

environmental impact, respectively. In contrast, EP provides 1.21% of the total environmental impact.

If one plans to employ the gas−liquid vulcanization waste acid disposal process, a proper management of these relevant disposal units should be analyzed to reduce environmental impact, such as human toxicity potential, and acidification potential. For a gas-liquid reinforcement unit, the highly-efficient removal of arsenic and other toxic elements can be realized within 5 min, and the removal rate can reach more than 99.0%. In addition, the amount of sulfide slag is much less than that in other disposal units. Therefore, compared with other disposal units, the gas−liquid reinforcement unit has low environmental impact values, especially for HTP. In the whole gas−liquid vulcanization waste acid disposal process, except for the gas−liquid reinforcement unit, the proportion of ADP in other disposal units is significantly higher than other environmental factors. The reason is that the catalytic stripping unit and neutralizing−evaporating−crystallization unit need high energy consumption. Although electrodialysis unit only needs to consume electric energy, its electric energy consumption is the highest compared with other disposal units. According to the calculated value of environmental impact in Fig. 5, the value of GWP is mainly related to the amount of CO_2, NO_2 and CH_4, etc. Compared with other disposal units, the electrodialysis unit has the large electric energy consumption, which leads to high global warming potential.

As shown in Fig. 6, the total environmental impact of traditional lime neutralization method in zinc smelting is 2.41×10^{-8}, which is 46 times as much as the value in gas−liquid vulcanization waste acid disposal technologies. The reason is that the gas−liquid vulcanization waste acid disposal process has almost achieved zero pollutant emission. For example, the light liquid from the electrodialysis unit and the slip liquid treated by the catalytic stripping unit can be reused in acid disposal process, and concentrated sulfuric acid meets the standard of industrial sulfuric acid, which can be sold as a product. The environmental environmental impact of vulcanization unit is nearly 73.5%, and the corresponding value for evaporating−crystallization unit is only 26.5%. The

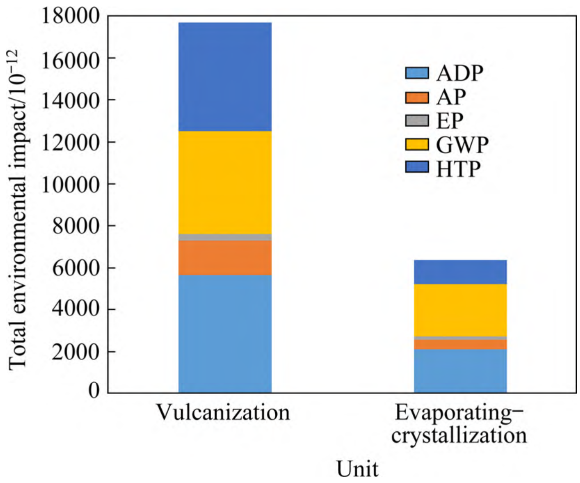

Fig. 6 Total environmental impacts of traditional lime neutralization method

total environmental impacts of ADP, GWP and HTP are particularly high with the values of 32.3%, 31% and 26.3%, respectively. Besides, AP and EP have the lower proportions of 8.6% and 1.83%, respectively.

In summary, from a comprehensive point of view, the major environmental impacts are ADP, GWP and HTP for both waste acid processes in which HTP and GWP are two dominated indicators. Therefore, from an environmental perspective, gas−liquid vulcanization waste acid disposal technologies might be a better choice than traditional lime neutralization process in zinc smelting.

In order to further compare the environmental impact of gas−liquid vulcanization waste acid disposal technologies and traditional lime neutralization method, the total environmental impacts of those two methods were calculated. The results show that the HTP in gas−liquid vulcanization waste acid disposal technologies is only 3.67% of traditional lime neutralization method. As for AP, gas−liquid vulcanization waste acid disposal technologies perform only 3.41% of traditional lime neutralization method. Similarly, the difference between gas-liquid vulcanization and traditional technologies is all below 1.5% in the other three indicators. In summary, gas−liquid vulcanization waste acid disposal technologies have an environmental advantage over all methods.

3.4 Sensitivity analysis

The sensitivity analysis was conducted to illustrate and analyze the variability of potential environmental burdens. In this study, the environmental benefits of treating waste acid in zinc smelting process are influenced by many factors. For new waste acid disposal technologies, there are four factors: sulphuric acid (30%), sodium hydrosulfide (70%), sodium carbonate and electricity. Sensitivity analysis was conducted with the input value of key processes as independent variable and the changing value of key categories as dependent variable. They were analyzed by reducing 10% of the consumption for each factor and the analysis results are given in Table 4. It should be noted that sensitivity calculation was performed in line with the functional unit of 1000 m^3 waste acid in zinc smelting.

As the results shown in Table 4, the influences of sulphuric acid (30%) and sodium carbonate on the changes of various environmental impact indicators are all below 0.02%. Therefore, the two factors can be ignored in gas−liquid vulcanization waste acid disposal technologies. In comparison, electricity and sodium hydrosulfide (70%) show evident changes on the impact for gas−liquid vulcanization waste acid disposal technologies. After reducing electricity by 10%, ADP, AP, EP, GWP and HTP are decreased by 4.24%, 3.21%, 4.93%, 5.75 and 5.48%, respectively, which results

Table 4 Sensitivity (%) of changes (variation of 10%) in environmental impacts of major input−output items to gas−liquid vulcanization waste acid disposal technologies

Category	Sulphuric acid (30%)	Sodium hydrosulfide (70%)	Sodium carbonate	Electricity
Global warming potential (GWP)	−0.04	0.36	0.20	5.70
Abiotic depletion (ADP)	−0.05	0.32	0.18	4.24
Acidification potential (AP)	0.30	0.13	0.14	3.31
Eutrophication potential (EP)	−0.02	0.37	0.16	4.93
Human toxicity potential (HTP)	0.00	0.06	0.43	5.48

in the decrease of total environmental impact by 23.55% in environmental benefit. Among these indicators, electricity has the greatest influence with 5.75% on GWP, which is significantly higher than other environmental impact indicators. This is due to the fact that the electricity requires vast consumption of hard coal, and thus, the amount of CO_2 produced is significantly higher than that of other indicators. When 10% of sodium hydrosulfide (70%) is reduced in gas−liquid vulcanization waste acid disposal technologies, ADP, AP, EP, GWP and HTP are decreased by 0.32%, 0.13%, 0.37%, 0.36% and 0.06%, respectively. It can be inferred that the consumption of electricity is the key effect of the overall environmental impact in gas−liquid vulcanization waste acid disposal technologies. Therefore, the decrease in electricity consumption is critical to reducing the overall environmental impact of gas−liquid vulcanization waste acid disposal technologies in zinc smelting. In addition, lower amount of sodium hydrosulfide (70%) can also help to reduce the environmental impact.

The sensitive of traditional lime neutralization method is given in Table 5. For traditional lime neutralization method, sodium sulfide (60%), sodium hydroxide (100%), limestone and electricity were chosen to be analyzed by reducing the consumption by 10%. It should be noted that as the impact of sodium hydroxide (100%) and electricity on the changes of various environmental impact indicators are less than 0.02%, they were not chosen to analyze.

In Table 5, It can be clearly seen that when the sodium sulfide (60%) is decreased by 10%, ADP, AP, EP, GWP and HTP also show reductions of 6.95%, 7.73%, 6.58%, 6.44% and 8.04%, respectively. That is to say, a 10% decrease in sodium sulfide (60%) consumption is responsible for the 35.74% of environmental benefit in total environmental impact. Particularly, when sodium sulfide (60%) is changed, the HTP performs the largest decrease of 8.04% among all environmental impact indicators. This result can be attributed to a large amount of sulfur slag (water content 50%), which is produced in the traditional lime neutralization method. However, sulfur slag (water content 50%) contains a large amount of arsenic and other heavy metals, and thus, HTP is the most prominent factor compared with other environmental impact indicators. For traditional lime neutralization method, the change of limestone consumption also cannot be ignored. When limestone is reduced by 10%, ADP, AP, EP, GWP and HTP are decreased by 1.42%, 1.16%, 1.59%, 1.74% and 0.95%, respectively. Considering the above results, the usage amount of sodium sulfide (60%) and limestone should be reduced in order to the cut down the overall environmental impact in traditional lime neutralization method.

3.5 Cost and profit analysis

The cost and income of the two waste acids treatment methods were estimated with rough economic analysis. Disposal cost of solid waste, such as neutralization residue and sulfur slag, is not considered. The main waste acids treatment expenses include chemical reagents and energy. The income is calculated on the basis of the products and byproducts to obtain the final profits. The unit price of every part is surveyed and obtained as the average market price from the main online trading platforms in China [33]. The data for economic comparison using the final cost, revenue and profit values of the two waste acids treatment processes are given in Table 6.

As shown in Table 6, the economic difference of these two waste acids treatment processes is very significant. For gas−liquid vulcanization waste acid

Table 5 Sensitivity (%) of changes (variation of 10%) in environmental impacts of major input−output items to traditional lime neutralization method

Category	Sodium sulfide (60%)	Sodium hydroxide (100%)	Limestone	Electricity
Global warming potential (GWP)	6.44	0.13	1.74	−1.88
Abiotic depletion (ADP)	6.95	0.00	1.42	−1.54
Acidification potential (AP)	7.73	0.00	1.16	−1.11
Eutrophication potential (EP)	6.58	0.23	1.59	−1.81
Human toxicity potential (HTP)	8.04	0.16	0.95	−0.95

Table 6 Comparison of cost and income of waste acids treatment method (1000 m^3 waste acid in zinc smelting was chosen as functional unit)

Disposal technology	Section	Subsection	Unit price	Quantity
Gas−liquid vulcanization waste acid disposal technologies	Cost	Sulphuric acid (30%)	0.53 RMB ¥/kg	9.91 kg
		Sodium hydrosulfide (70%)	4.80 RMB ¥/kg	17.05 kg
		Sodium carbonate	2.45 RMB ¥/kg	26.52 kg
		Electric power	0.73 RMB ¥/(kW·h)	434.98 kW·h
	Income	Sodium sulfide	0.24 RMB ¥/kg	3450 kg
		Calcium fluoride (water content 20%)	0.01 RMB ¥/kg	4000 kg
		calcium chloride (water content 20%)	0.02 RMB ¥/kg	700 kg
Traditional lime neutralization method	Cost	Sodium sulfide (60%)	1.50 RMB ¥/kg	23580.81 kg
		Sodium hydroxide (100%)	1.60 RMB ¥/kg	1318.18 kg
		Limestone	0.30 RMB ¥/kg	104843.31 kg
		Electric power	0.73 RMB ¥/(kW·h)	203 kW·h
	Income	−	−	−

disposal technologies, the expenses and income of disposing 1000 m^3 waste acid in zinc smelting are RMB ¥ 152.38 and 127.23, respectively. So, the total cost of disposing 1000 m^3 waste acid is only RMB ¥ 25.15. However, the traditional lime neutralization process without products or byproducts has no profit and needs to spend RMB ¥ 689.33, which is nearly 27 times that of the new waste acid disposal technologies. The traditional lime neutralization process uses a large amount of chemical reagents, such as sodium sulfide (60%) and sodium hydroxide, and there is no product, so the disposal cost is higher than that of gas−liquid vulcanization waste acid disposal technologies. Based on the calculated cost and income, the optimal choice for profit is gas−liquid vulcanization waste acid disposal process.

4 Recommendation

Currently, conserving resources and protecting environment are two significant issues in China. The life cycle assessment (LCA) was applied successfully in this study, and the results showed that traditional lime neutralization method brings a serious environmental impact. In comparison, the new waste acid disposal processes show strong economic advantages when on-site pollution treatment costs are included in the analysis. In the long-term future, the gas−liquid vulcanization waste acid disposal process shows a promising prospect for its reduced environmental impact, which is deem to be a compatible choice for the local residents.

Therefore, Chinese government should regulate behaviors of enterprises through laws and institutions, and then gradually optimize and upgrade the waste acids treatment industry. For better reducing environmental pollution, enterprises should be encouraged to make technological innovations and improvements especially in waste acid disposal stage, such as using gas−liquid vulcanization waste acid disposal process instead of traditional lime neutralization method, which can not only reduce environmental pollution but also save disposal cost. Waste acid recovery and resource utilization are arduous projects. We must not only improve the waste acids treatment process, but also develop circular economy. Besides, the combination of upstream and downstream industrial chains and strengthening the joint cooperation between enterprises ought to be also promoted for a new situation of waste acid resource utilization in China.

5 Conclusions

(1) The significant environmental impacts of gas−liquid vulcanization waste acid disposal technologies are ADP, GWP and HTP. The

evaporating−crystallization unit and electrodialysis unit are the two main processes which cause environmental impacts on waste acid treatment in gas−liquid vulcanization waste acid disposal technologies.

(2) For traditional lime neutralization method, vulcanization unit is the dominated environmental impact processes. According to the analysis, traditional lime neutralization method has greater environmental impact than gas−liquid vulcanization waste acid disposal technologies in zinc smelting. Besides, the total environmental impact indicates that gas−liquid vulcanization waste acid disposal technologies can bring more environmental benefits.

(3) From the sensitivity analysis, the consumption of electricity is most sensitive factor in gas−liquid vulcanization waste acid disposal process, followed by the use of coal, while sodium sulfide (60%) is the most sensitive factor in traditional method, followed by the usage amount of limestone.

(4) From the cost and profit analysis, the total cost of disposing a functional unit waste acid for traditional lime neutralization process is nearly 27 times that of the gas−liquid vulcanization waste acid disposal technologies.

(5) LCA method can provide a reliable reference value for the optimization of waste acid treatment, and also illustrate the advantage of new waste acid treatment process in zinc smelting.

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锌冶炼污酸处理的生命周期评价

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摘 要：采用生命周期评价方法对锌冶炼过程中的两种污酸处置工艺进行评价和对比。结果表明，气液硫化法的环境影响主要为人体毒性、非生物资源耗竭和全球变暖潜值，这些环境问题主要由中和−蒸发−结晶与电渗析单元造成；同时传统石灰石中和法中的硫化单元也是环境影响的主要来源，且石灰石中和法的总环境影响比气液硫化法高很多。结合敏感性分析发现，气液硫化法和石灰石中和法敏感度因子均为电和硫化钠(60%)，且石灰石中和法处置单位污酸的总成本约为气液硫化法的 27 倍。

关键词：锌冶炼；污酸处理；生命周期评价；环境影响

(Edited by Bing YANG)