Assessment of Life Cycle Environmental Benefits in Monosodium Glutamate Production in China

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Research Article

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Abstract

Purpose

As a process with high water consumption, high energy consumption and high pollutant discharge, monosodium glutamate (MSG) production has long attracted the attention of environmental protection authorities. In view of its significant environmental influence and enormous output, life cycle environmental impacts of MSG should be assessed to identify environmental hot spots and promote environmental improvements, and to update the life cycle inventory database of MSG production.

Methods

A life cycle assessment (LCA) framework is conducted to evaluate the environmental impacts of MSG production by the use of eBalance software. In addition, the environmental impacts associated with the application of typical cleaner production techniques over the past decade in MSG production are evaluated by LCA to quantitatively demonstrate the importance of implementing cleaner production measures.

Results and discussion

The results indicate that maize planting and tail liquid utilization have the largest environmental impacts within the life cycle of MSG. The former is the most important driver of impacts such as eutrophication (90.37%), respiratory inorganic formation (34.04%) and primary energy demand (26.60%). The latter contributes to 96.72% of the photochemical oxide formation and 20.12% of the global warming potential. In addition, glutamate extraction and refining processes also contribute significantly to the global warming potential, acidification and respiratory inorganics. The results also show that the application of cleaner production technologies over the past decade has driven the reductions in photochemical oxide formation (92.40%) and water use (66.00%).

Conclusion

Based on the research findings, several suggestions, such as green raw material utilization, green supply chain construction and industrial symbiosis network establishment, are proposed to further reduce the overall environmental impacts of MSG.

1. Introduction

Monosodium glutamate (MSG), the sodium salt of glutamic acid, is the most produced and consume food flavor enhancer worldwide. Glutamate (GA), as a constituent of many proteins, exists extensively in animal and vegetable proteins such as soybean, wheat, and kelp, as well as in many common foods (Ault and Addison 2004). In addition to producing flavor enhancers, GA is widely used in pharmaceutical and chemical intermediates and cosmetics (Williams 2005).

The production of MSG reached 4.7 million tons worldwide in 2018, and production in China accounted for approximately 76% of the total capacity, which made China the largest MSG producer and exporter. The production methods of MSG include extraction from natural materials (such as soybean and beets), chemical synthesis, enzymatic catalysis and fermentation (Ault and Addison 2004). Among these methods, fermentation is the most popular due to its low cost and high security (Zhang et al. 2012). In fermentation methods, grain starches, such as wheat and maize starch, are first used to produce glucose, and the glucose is then fermented with a special strain of yeast to produce GA. However, considerable energy and freshwater are consumed in MSG production, and a large amount of wastewater with a high chemical oxygen demand, high ammonia nitrogen and abundant sulfate is produced (Xue et al. 2008).

In view of its significant environmental influence and enormous output, life cycle environmental impacts of MSG should be assessed to identify environmental hot spots and promote environmental improvements. A life cycle assessment (LCA) method is ideal for such objectives.

LCA is a holistic approach for quantitatively evaluating the potential environmental impacts of a product (UNEP 2011). This effective method has been used to evaluate the environmental burdens of industrial products such as methanol, biofuels, lead-acid batteries, offset paper, and ceramic tiles (Li et al. 2018; Liu et al. 2015; Lopes Silva et al. 2015; Rocha et al. 2014; Ye et al. 2018). Such a method can not only identify the environmental hotpots of production processes but also provide data to support future energy conservation and emission reductions for industrial enterprises (Finnveden et al. 2009; KlöPffer 2006). However, few LCA studies have focused on the amino acid products of fermentation, let alone MSG products.

Cleaner production is an efficient environmental protection measure that can reduce harm to human beings and the environment and promote sustainable development by continuously improving management, technological progress, and the efficiency of resource utilization and reducing the generation and discharge of pollutants (Cagno et al. 2005; F.J. and R.M. 2020; Fresner 1998; Zarker and Ken 2013).

The concept of cleaner production (CP) was first introduced in China in 1993 (Hicks and Dietmar 2007), and after more than 20 years of development, CP has made an important contribution to the alleviation of the environmental pressure associated with high-polluting industries (Bai et al. 2015; Gong et al. 2016; Li et al. 2016; Meng et al. 2015); naturally, the MSG industry has been influenced by this approach (Dong et al. 2018; Ping et al. 2015).

The Ministry of Environmental Protection of China issued a CP standard for the MSG industry in 2008 to force MSG enterprises to implement CP measures and achieve the corresponding energy conservation and emission reduction targets. Dong et al. (Dong et al. 2018) reviewed the common pollution control technologies, CP measures and associated mechanisms in the MSG industry in China over the past 10 years and emphasized the contribution of CP strategies to environmental improvement based on quantitative indicators such as wastewater discharge reductions, energy conservation reductions and conversion rates. However, the above indicators can partly but not entirely reflect the environmental impacts of CP measures on the life cycle processes of MSG production. The LCA method has been effectively applied to evaluate the environmental effects of CP measures in some industries, such as the iron casting industry (Yilmaz et al. 2014), automotive industry (Lopes Silva et al. 2018), and irrigated carrot production (Lopes et al. 2018). Therefore, the LCA method is used in this article to evaluate CP performance in the MSG industry.

The objective of our study is to evaluate the environmental effects of MSG products with an LCA method to fill the current life cycle inventory data gaps and estimate the environmental contributions of CP measures in the MSG industry.

The remainder of the article is organized as follows. Section 2 introduces the main CP measures applied in the MSG industry. Section 3 presents the life cycle assessment process, and the assessment results are shown in Section 4. The discussion regarding the contributions of CP technologies and suggested topics for future research is presented in Section 5. Finally, the conclusions are given in Section 6.

2. Key Cp Measures In The Msg Industry

Currently, MSG is mainly produced by fermentation, which is the most popular method in China, with maize and other starch-containing grains as the raw materials. The starch in grains is converted into glucose, which is the substrate of GA fermentation; then, the MSG is through reactions between the extracted GA and Na_2CO_3. The MSG production process includes five phases: starch production, glucose (GLU) production, GA fermentation, GA extraction and refinement (ER), and waste disposal (Fig. 1). Because the specific production processes have been described in detail by Dong et al. (Dong et al. 2018), only the typical CP technologies of each phase are introduced in this article. Three CP technologies that have had the greatest impacts on the economic and environmental benefits of MSG production over the past 10 years are introduced: high-performance temperature-sensitive strain fermentation technology, concentrated isoelectric continuous extraction technology and tail gas treatment technology in mixed fertilizer production with the spraying and granulation of fermentation tail liquid.

2.1 Fermentation technology to replace biotin suboptimal strains with temperature-sensitive strains

Suboptimal strains are biotin auxotrophic strains, which can promote GA metabolism flow by controlling the carbon dioxide fixation reaction in the tricarboxylic acid cycle (TCA) and play a key role in acid production by bacteria. Most temperature-sensitive strains are genetically mutated strains that can grow under normal temperature conditions. If the temperature is higher than a certain value, the growth of the bacteria will stop, and only the acid production process will continue. If temperature-sensitive strains are used instead of suboptimal strains, the metabolic flux of GA be greatly improved, and the cell membrane permeability mechanism can also be relieved by increasing the temperature. Compared to the results with traditional suboptimal biotin technology, the GA yield is increased from 120 g/L to 210 g/L, the conversion rate is increased from 55% to 69%, and the main byproducts are reduced by more than 99% with temperature-sensitive bacterial fermentation technology. In addition, water and electricity consumption can be reduced by 21.0% and 23.8%, respectively.

2.2 Extraction technology for replacing isoelectric crystallization and ion exchange with concentrated isoelectric continuous extraction

The isoelectric crystallization and ion exchange (IEIE) process, as a traditional extraction method widely used in most MSG enterprises 8 years ago in China, includes two phases: isoelectric crystallization and ion exchange. Isoelectric crystallization involves adding concentrated H_2SO_4 and seed crystals to the fermentation broth to reach the isoelectric point of GA. Crude GA was obtained after stirring, letting the mixture stand and centrifuging, and the extraction rate of GA was 78-80%. However, 20% GA remained in the mother liquor after isoelectric extraction, and the ion exchange resin was used in further GA extraction to increase the total GA extraction rate to 94-95%. However, 120 kg of liquid ammonia and 850 kg of concentrated H_2SO_4 were consumed to extract 1 t of GA in the ion exchange process. Additionally, during the regeneration of the ion exchange column, a large amount of high-NH_4^+-N-containing wastewater is generated.

In the continuous process of concentrated isoelectric extraction, the fermented broth is first concentrated using a multi-effect evaporator, and H_2SO_4 is then added to adjust the pH value to 3.22, which results in the continuous crystallization of GA; next, GA can be separated after centrifugation. The remaining tail liquid is concentrated and desalted to produce byproducts such as $(NH_4)_2SO_4$ and fertilizer. The crystals are washed and then transferred to the crystal conversion process to release the impurities and pigments entrained during crystallization. This process will cause a 3-4% loss of GA, causing the total yield of GA to be 88%-90%. Although the extraction rate of GA in the continuous process of concentrated isoelectric extraction is 5% lower than that in the IEIE process, the consumption of concentrated H_2SO_4 is reduced by 53%, and no liquid ammonia is consumed, which reduces the production of high-NH_4^+-N-containing wastewater by 90%.

2.3 Tail gas treatment technology in mixed fertilizer production with spraying and the granulation of fermentation tail liquid

After byproducts such as GA, $(NH_4)_2SO_4$ and bacterial protein are extracted, the fermentation tail liquid still contains a large amount of organic compounds, which can be directly sprayed and granulated to produce fertilizer with hot gas at 500-600°C. This CP approach has been widely used in China since it was popularized in 2004. However, due to the large amount of volatile organic compounds (VOCs) in the tail gas produced in the spray granulation process, large amounts of fumes that have strong odors and poorly diffuse are emitted, causing serious air pollution. Tail gas pollution was an important bottleneck that restricted the development of the MSG industry until 2010. Then, a key CP method in which a new type of electrostatic separation equipment made of nonmetal conductive composite material with high temperature, corrosion and electric field resistance was used to treat VOC tail gas in the spray granulation process. The VOC removal rate with this new approach can reach 95%, which is 55% higher than that of the previous process (tail gas washing process).

3. Methodology And Data

3.1 Functional unit and system boundaries

The functional unit in this article is 1 t of MSG; all the raw material inputs, the product and byproduct outputs, and energy consumption are based on this functional unit. A cradle-to-gate approach is adopted to determine the system boundaries (Fig. 1) in which all the processes involving raw materials and energy production, the transport of raw materials, on-site emissions, and waste disposal associated with MSG production are included.

3.2 Life cycle inventory and data sources

The life cycle inventory results are listed in Table 1. All the raw materials (e.g., maize, sulfur acid, ammonia, water, electricity, and steam), energy consumption processes, transportation processes for raw materials, on-site emissions (e.g., waste water, carbon dioxide and VOCs), and waste disposal processes are based on the functional unit. For byproducts such as fertilizers and ammonium sulfate produced during MSG production, a value distribution method is used to allocate raw materials and energy consumption requirements.

The inventory data in this article are based on field survey data from one of the top-3 MSG manufacturers in China. The background data (e.g., hydrochloric acid, sulfur acid and liquid ammonia data) are obtained from the Chinese reference life cycle database (CLCD), which covers more than 400 materials in China. The background inventory data for maize farming, harvesting and processing were obtained from the Ecoinvent database.

Two scenarios are designed to compare the environmental impacts of the three CP abovementioned methods in the MSG industry. In Scenario 1, the CP methods are all implemented (the inventory data are based on the production data in 2019). In Scenario 2, none of the CP methods are implemented (the inventory data are based on the CP audit report, annual environmental report, literature, and clean production implementation technical plan of the Ministry of Industry and Information Technology).

3.3 Life cycle impact assessment

The life cycle impact assessment process converts the inventory data into comparable environmental impact targets and evaluates the results based on an impact assessment method. Many well-established assessment models and methods are popular in LCIA, such as the ReCiPe model, IMPACT 2002+ model, CML2002 model, and Eco-indicator99 (Matthews et al. 2014).

Seven impact categories, including the primary energy demand (PED), acidification (AP), eutrophication (EP), global warming potential (GWP), photochemical oxide formation (POFP), respiratory inorganics (RI), and water use (WU), are selected to evaluate MSG in this article. All the impact assessment processes are from eBalance software. Additionally, the characterization factors of AP and EP are taken from CML2002 (Curran and Ann 2012), the characterization factor of GWP is from IPCC2007 (Forster et al. 2007), the characterization factor of POFP is based on ReCiPe (Goedkoop et al. 2009), and the characterization factor of RI is taken from IMPACT2002+ (Margni et al. 2003). The normalized results are based on the normalized reference for China in 2010 (CN-2010), which is based on emission data from the China Environmental Statistical Yearbook and statistics from the International Institute for Applied Systems Analysis.

4. Results

Table 2 and Table 3 list the results of the characterization factor and percentage by stage and the normalization values and percentage by stage of 1 t of MSG production in Scenario 1, respectively. The contribution of each stage to the characterization factor is shown in Fig. 2. The results showed that POFP was the largest environmental impact factor in MSG production, followed by PED, GWP, AP, EP, WU and RI. From the perspective of the production process, the tail liquid treatment process is associated with the largest potential environmental impact, followed by the maize planting and harvesting process. The results for specific environmental impact factors are as follows.

Photochemical oxide formation. This process totals 4.95E+01 kg of NMVOCeq for 1 t of MSG throughout the life cycle, 96.7% of which is contributed by the fermentation tail liquid treatment stage. In this stage, the tail liquid is utilized to produce organic fertilizer by spraying granulation, which generates a mass of VOCs at a high temperature; however, the tail gas cannot remove the VOCs completely with the currently available treatment technologies.

Primary energy demand. The potential environmental impact on PED is 1.09E+05 MJ, and the glutamate fermentation process contributes the most (35.42%) to this total. This result is mainly due to the heavy use of liquid ammonia in the fermentation process, and the corresponding PED contribution accounts for 74.11% of the total. In addition to the glutamate fermentation process, the maize planting and harvesting process contributes to 26.60% of the total, principally from the energy consumption of motor vehicles during transport, agricultural machinery tillage, and irrigation. From the perspective of key materials, the mining and transportation of raw coal contributes the most to the PED, accounting for 72.3% of the total.

Global warming potential. The potential environmental impact on GWP is 3.14E+03 kg of CO_2eq, 32.92% of which is from the ER process of MSG. The contributions are mainly indirect emissions from the production of the raw materials used in the ER process, such as caustic soda liquid and concentrated sulfuric acid, and on-site emissions from the production of steam. In addition, the environmental impact on GWP from the glutamate fermentation stage accounts for 23.35% of the total because of the utilization of steam and liquid ammonia. From the perspective of key materials, the largest contributor is steam, which accounts for 34.90% of the total, followed by the tail liquid (15.90%).

Acidification. The AP totals 1.25E+01 kg SO_2eq for 1 t of MSG throughout the MSG life cycle, and the ER process of MSG contributes the most to this total (71.03%). The utilization of concentrated sulfuric acid and caustic soda liquid in this process leads to this result. Accordingly, the key material that contributes to AP is concentrated sulfuric acid, accounting for 68.41% of the total.

Eutrophication. The environmental impact on EP is 2.97E+00 kg PO_4^{3}-eq, 90.37% of which is from maize planting and harvesting because of the broad-scale use of nitrogen-phosphorous fertilizers in the planting process.

Water use. The consumption of freshwater used in the production of 1 t of MSG is 1.68E+04 kg, 42.20% of which is from the ER process. The indirect use of concentrated sulfuric acid and the on-site freshwater use in this stage contribute to 38.33% and 38.26% of the total potential water utilization in the ER process, respectively.

Respiratory inorganics. The environmental impact on RIs is 1.71E+00 kg PM2.5eq, 51.28% of which is from the ER process due to the utilization of concentrated sulfuric acid and caustic soda liquid. The key materials for RI formation are concentrated sulfuric acid, maize and caustic soda liquid, which account for 34.31%, 28.23% and 16.92% of the total RI mass, respectively.

5. Discussion

With China becoming the largest producer of MSG, scientific evaluations of the environmental effects of MSG production are crucial for energy conservation, emission reductions and the green development of the MSG industry. Additionally, life cycle environmental impact factors are more comprehensive and convincing than some traditional energy saving and emission reduction factors (such as material reduction and pollution reduction) in evaluating the environmental effects of CP technologies.

5.1 Environmental impact of the applied CP technologies

The potential environmental impacts of producing 1 t of MSG without applying the abovementioned three CP methods (Scenario 2) are assessed in this article. The results in Fig. 3 show that compared with those in Scenario 2, all of the characteristic impact factors are lower under the current production technology conditions (Scenario 1). Among these factors, the value of POFP decreases the most by 92.40%, followed by those of WU, AP, RI, PED, GWP, and EP, which decrease by 66.00%, 38.12%, 27.13%, 25.36%, 22.42%, and 21.31%, respectively.

In terms of the production process and specific indicators, the POFP of the tail liquid treatment process decreased the most, from 6.45E+02 kg NMVOC to 4.29E+01 kg NMVOC. The main reason for this change was the implementation of the CP technology mentioned in Section 2.3. This technology increased the removal efficiency of the VOCs in the exhaust gases from 45% to 95%, which prevented the MSG companies from being shut down by environmental authorities.

There is also a significant decline in the WU in the ER process by 81.41% because of the application of the CP technology discussed in Section 2.2. The process of extracting GA via the isoelectric crystallization and ion exchange method requires a large amount of water to wash the resins, but this consumption issue is avoided in the concentrated continuous isoelectric method. Moreover, the concentrated continuous isoelectric method can reduce the heavy discharge of waste water; as a result, the EP value of the ER process decreased by 71.70%. In addition, the AP and PED values in the ER process declined by 43.81% and 40.84%, respectively, because of the reductions in concentrated sulfuric acid and liquid ammonia in the concentrated continuous isoelectric method. Although the extraction rate of glutamate in the concentrated continuous isoelectric method (90%) is lower than that in the isoelectric crystallization and ion exchange method (95%), the overall environmental effects are much lower.

The largest rate of decrease in the characteristic impact factor for the fermentation process is for the PED (23.01%) because the temperature-sensitive fermentation bacteria increased the acid yield of glucose with the CP technology mentioned in Section 2.1.

5.2 Opportunities for improvement

The potential environmental impact of 1 t of MSG is assessed in this article. The results show that maize and tail liquor are the two most important contributors to the related environmental effects. Maize planting and harvesting contributed to 90.37% of EP, 34.04% of RI, 26.60% of PED, and 19.19% of WU. Tail liquor utilization contributed to 96.72% of POFP and 20.12% of GWP.

A total of 2.12 tons of maize is used to produce 1 t of GA through maize-starch conversion (conversion rate is 70%), starch-glucose conversion (conversion rate is 98%), glucose-glutamate conversion (conversion rate is 65%) and glutamate extraction and refining (extraction rate is 90%). All the conversion and extraction rates except the GA extraction rate have reached maximums with the currently used technologies. Although the extraction rate of GA based on the isoelectric crystallization and ion exchange method can reach 95%, the process has been gradually eliminated due to the production of a large amount of washing wastewater and separation wastewater. Therefore, the only way to reduce the potential environmental impact of maize is to focus on the maize planting and harvesting process in the next few years. The environmental effects of this process mainly come from the emissions associated with irrigation, transportation energy consumption and the application of pesticides and fertilizers. Hence, the main measures used to reduce the environmental effects of maize planting should focus on targeted seed selection, water-saving irrigation, scientific fertilization and pest control in the future.

The environmental contribution of the fermentation tail liquor is mainly due to VOC emissions and energy consumption by the spraying granulation process. Although the CP technology used for VOC removal with electrostatic separation equipment has increased the removal rate to 95%, the remaining 5% of small VOCs still cannot be removed. Even if some new technologies can remove this 5% of VOCs, the high economic cost would increase the burden on MSG enterprises. Therefore, low-temperature tail liquid utilization technology needs to be promoted to avoid VOC generation and high energy consumption.

In addition to maize and tail liquor, the contributions of concentrated sulfuric acid and liquid ammonia to the environment are also significant. The contributions of concentrated sulfuric acid to AP and RI are 58.51% and 24.91%, respectively, and the contribution of liquid ammonia to PED is 26.25%. Concentrated sulfuric acid mainly provides H^+ and regulates pH for glutamic acid extraction. Because sulfate will not corrode containers (compared with hydrochloric acid) and is affordable, it is the best choice at present. Therefore, greener sulfuric acid production is the optimum choice for reducing the environmental impact of the full life cycle. For example, the application of a high-efficiency vitriol catalyst and improvements in desulfurization technology are effective measures that could reduce sulfur dioxide emissions in the sulfuric acid production process (Oni et al. 2018). Liquid ammonia mainly provides a nitrogen source and regulates pH in the glutamate fermentation process. Because of its high nitrogen content, liquid ammonia is currently the most ideal nitrogen source. Hence, reducing the environmental contributions of liquid ammonia production, especially those related to energy consumption, is the best way to improve the environmental effects of the MSG life cycle. The effective methods for reducing energy consumption during ammonia production include continuous pressure coal gasification, trace carbon removal and the use of evaporative cooling technologies (Chao et al. 2012).

The above analysis shows that the implementation of CP technologies has effectively reduced the environmental effects of the MSG industry over the past ten years, but there is little room to improve the environmental impacts of MSG enterprises through CP technologies (alternatively, new CP technologies are still in the research stage), except by addressing the tail liquid utilization stage. Therefore, in addition to improvements within MSG enterprises, life cycle theory should be applied to realize the sustainable green development of the MSG industry, as witnessed for the green manufacturing system integration projects organized by the Ministry of Industry and Information Technology (MIIT) of the People's Republic of China. The projects aim to meet the goals of "Made in China 2025" by establishing green design platforms, improving key green technologies and constructing green supply chains. Specific to the MSG industry, green raw materials (such as maize, sulfuric acid and liquid ammonia) and green supply chain construction can significantly reduce the environmental impact on the whole life cycle. Moreover, an industrial symbiosis network of "maize planting-fermentation-biological byproducts-agricultural planting" can be constructed to extend the industrial chain and improve the utilization rate of resources, and a typical circular economy pattern is successfully built focused on the MSG manufacturers in East China.

6. Conclusion

The MSG industry has long attracted the attention of environmental protection authorities because of the high pollution rate and high water consumption. However, the implementation of CP technologies has significantly mitigated the environmental pollution from the MSG industry in China over the past decade. However, with the increasing requirements of environmental protection, further improving the environmental status of the MSG industry remains a problem. In this article, the LCA method is used to evaluate the contributions of CP technologies to the environmental benefits observed in the past decade and to assess the life cycle-based environmental impact of MSG under the current production conditions. Additionally, potential future improvements were identified.

The results show that the application of CP technologies in the past decade has contributed most to reductions in the environmental impacts on POFP and WU, and the greatest contributors under the current MSG production conditions are POFP, PED and GWP. The green development of the MSG industry can only be realized through the joint implementation of CP measures inside enterprises, green supply chain construction and industrial symbiosis network establishment. The LCIA results in this article not only fill a gap in the current MSG product inventory data but also provide a data reference and theoretical support for MSG enterprise managers and policy makers regarding future green development.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

All data generated or analysed during this study are included in this published article.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

F Y contributed to the conceptualization, methodology, formal analysis, and writing - original draft;

D G contributed to the investigation and data curation;

Zd Z contributed to the investigation;

L Z contributed to the writing - review & editing;

Lh Z contributed to the conceptualization, methodology, supervision and project administration.

All authors read and approved the final manuscript.

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Tables

Table 1. Life cycle inventory for 1 t of monosodium glutamate

Process unit	Parameters	Unit	Scenario 1	Scenario 2
Starch milk production	Product and resource inputs			
	maize	t	2.12E+00	2.40E+00
	water	t	4.06E+00	4.61E+00
	electricity	kwh	2.24E+02	2.54E+02
	steam	t	1.18E+00	1.34E+00
	sulfur dioxide	kg	3.89E+00	4.43E+00
	Wastes to be treated and emissions			
	Waste water	m^3	9.21E-03	1.05E-02
Glucose production	Product and resource inputs			
	Starch milk	t	1.49E+00	1.70E+00
	water	t	3.26E-01	3.71E-01
	electricity	kwh	1.62E+01	1.84E+01
	steam	t	4.96E-01	5.66E-01
	Wastes to be treated and emissions			
	Waste water	m^3	2.98E-02	3.39E-02
GLU fermentation broth production	Product and resource inputs			
	glucose	t	1.42E+00	1.62E+00
	water	t	1.79E+00	2.03E+00
	electricity	kwh	2.06E+02	2.41E+02
	steam	t	1.88E+00	2.33E+00
	compressed air	m^3	1.51E+00	2.02E+00
	liquid ammonia	kg	2.38E+02	3.14E+02
	sodium hydroxide	kg	2.21E+01	2.92E+01
	Wastes to be treated and emissions			
	waste water	m^3	8.70E-02	9.80E-02
MSG extraction and refinement	Product and resource inputs			
	fermentation broth	t	9.28E-01	8.77E-01
	water	t	2.54E+00	2.92E+01
	electricity	kwh	1.46E+02	1.46E+02
	steam	t	3.10E+00	3.19E+00

	concentrated sulfuric acid	kg	3.29E+02	6.21E+02
	Sodium hydroxide	kg	2.19E+02	2.19E+02
	liquid ammonia	kg	0.00E+00	8.77E+01
	polyethylene	kg	1.17E+01	1.17E+01
	hydrochloric acid	kg	1.28E+00	1.28E+00
	flocculants	kg	7.09E-01	2.19E+00
	Wastes to be treated and emissions			
	waste water	m^3	0	2.19E+00
Tail liquid utilization	Product and resource inputs			
	tail liquid	t	2.27E+00	7.31E+00
	electricity	kwh	9.50E+01	1.43E+02
	steam	t	5.12E-01	7.68E-01
	coal	t	2.19E-01	3.29E-01
	Wastes to be treated and emissions			
	carbon dioxide	t	4.09E-01	6.14E-01
	VOCs	kg	4.57E+01	6.16E+02
	sulfur dioxide	kg	4.39E-01	5.48E-01
	PM2.5	kg	2.19E-03	3.29E-03

Table 2. Characterization factor and percentage by stage for 1 t of MSG production

LCI impact	Characterization factor	Percentage by stage					
		Maize farming	Starch milk production	Glucose production	GLU fermentation broth production	MSG extraction and refinement	Tail liquid utilization
PED	1.09E+05 MJ	26.60%	4.65%	2.14%	35.42%	17.96%	13.23%
GWP	3.14E+03 kg CO_2eq	12.87%	7.34%	3.40%	23.35%	32.92%	20.12%
AP	1.25E+01 kg SO_2eq	11.88%	2.86%	0.77%	7.59%	71.03%	5.87%
EP	2.97E+00 kg PO_4^{3-}eq	90.37%	0.47%	0.44%	2.76%	5.44%	0.52%
POFP	4.95E+01 kg NMVOCeq	1.07%	0.08%	0.02%	0.25%	1.86%	96.72%
RI	1.71E+00 kg PM2.5eq	34.04%	1.96%	0.57%	7.96%	51.28%	4.19%
WU	1.68E+04 kg	19.19%	19.79%	2.32%	15.30%	42.20%	1.20%

Table 3. Normalization factor by stage for 1 t of MSG production

Stage	PED	GWP	AP	EP	POFP	RI	Water use	Stage total
Maize farming	3.29E-10	3.83E-11	4.08E-11	7.15E-10	5.63E-11	3.09E-11	5.31E-12	1.22E-09
Starch milk production	5.75E-11	2.19E-11	9.80E-12	4.00E-12	4.23E-12	1.79E-12	5.47E-12	1.05E-10
Glucose production	2.64E-11	1.01E-11	2.65E-12	3.60E-12	1.23E-12	5.20E-13	6.40E-13	4.51E-11
GLU fermentation broth production	4.38E-10	6.96E-11	2.61E-11	2.18E-11	1.34E-11	7.23E-12	4.23E-12	5.80E-10
MSG extraction and refinement	2.22E-10	9.80E-12	2.44E-10	4.31E-11	9.79E-11	4.66E-11	1.20E-11	6.75E-10
Tail liquid utilization	1.64E-10	5.99E-11	2.02E-11	4.11E-12	5.10E-09	3.81E-12	3.31E-13	3.05E-09
Total	1.24E-09	2.10E-10	3.44E-10	7.92E-10	5.27E-09	9.09E-11	2.80E-11	5.67E-09

Figures

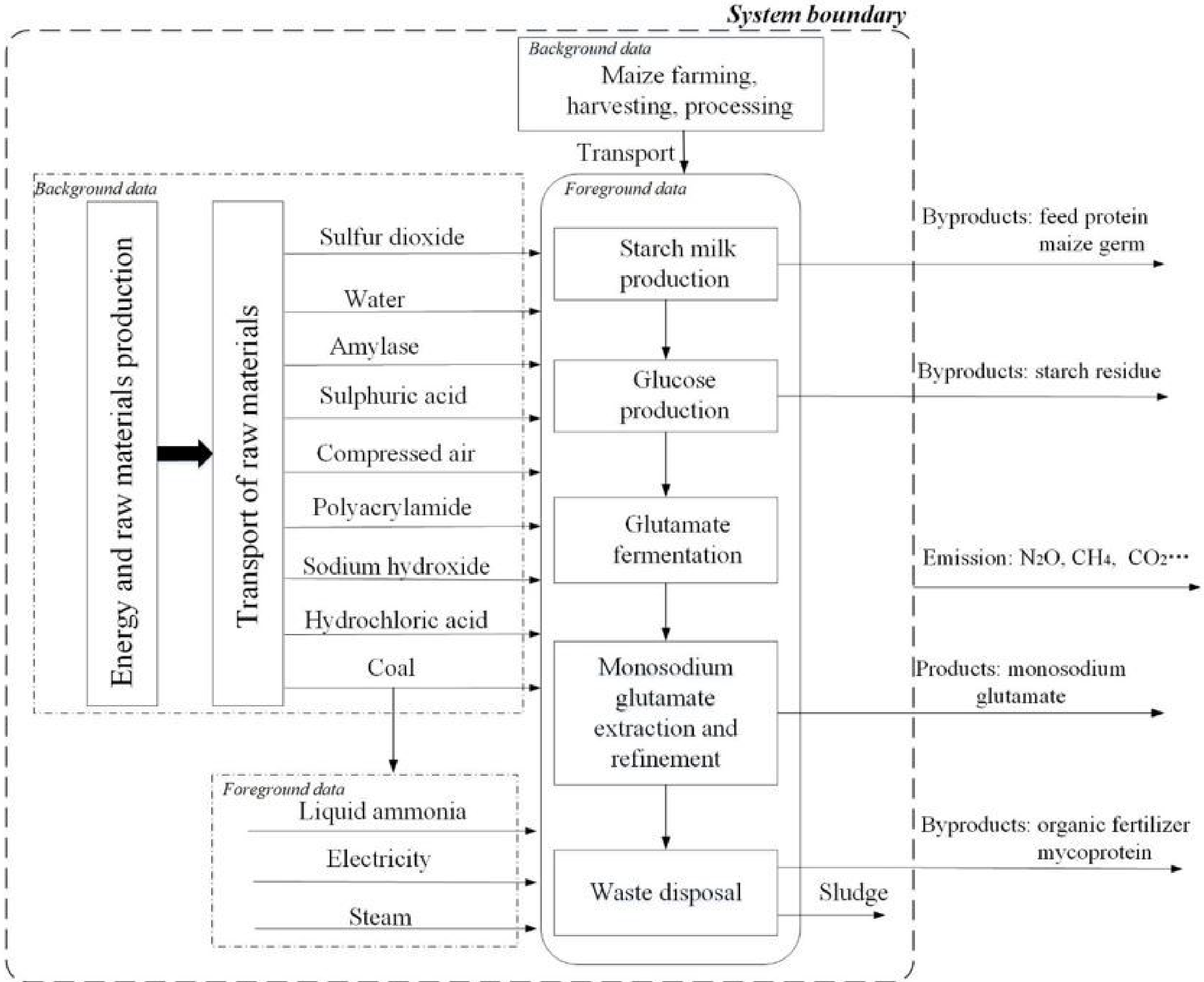

Figure 1

System boundaries and material flows

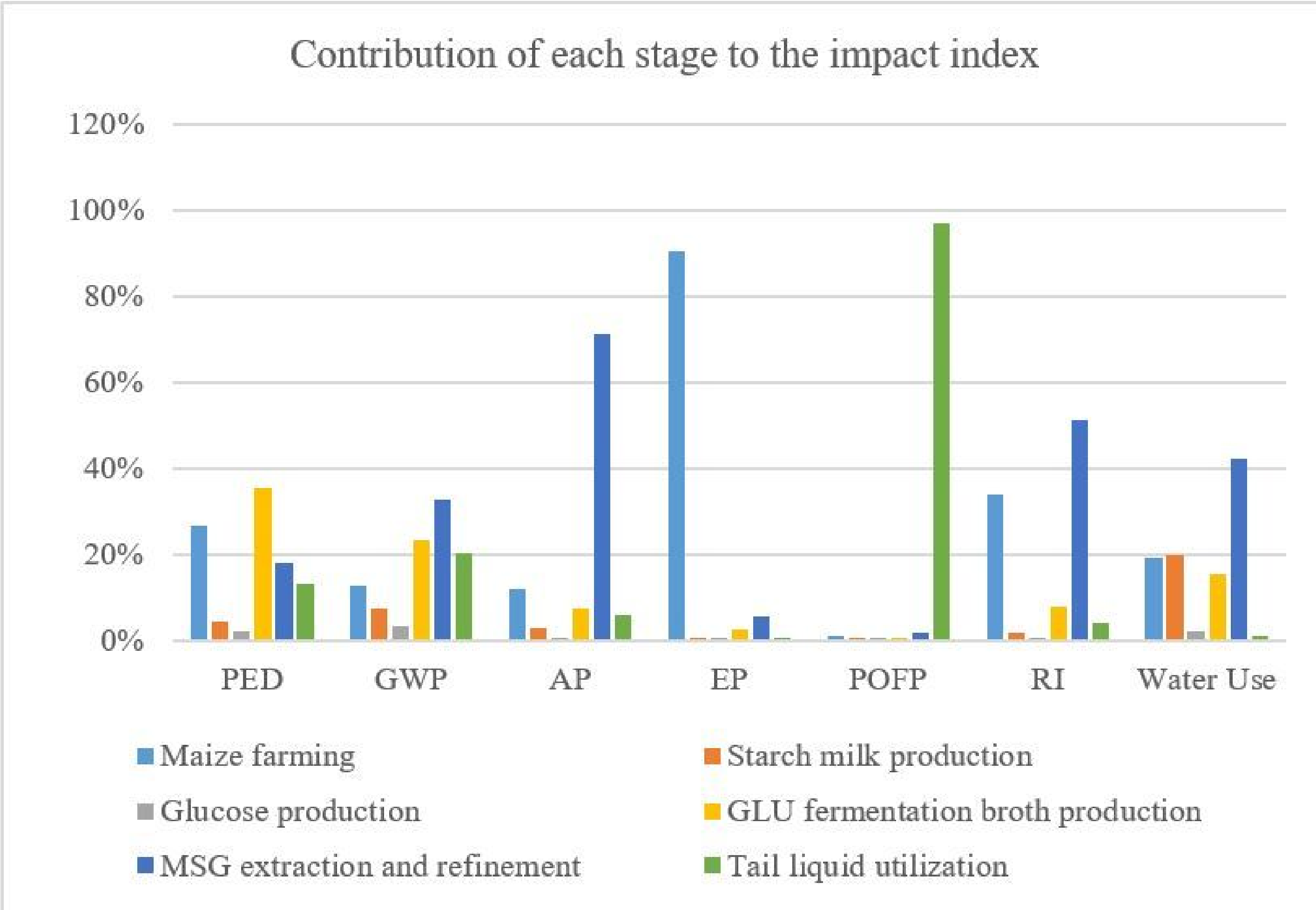

Figure 2

Contribution of each stage to the characterization factor

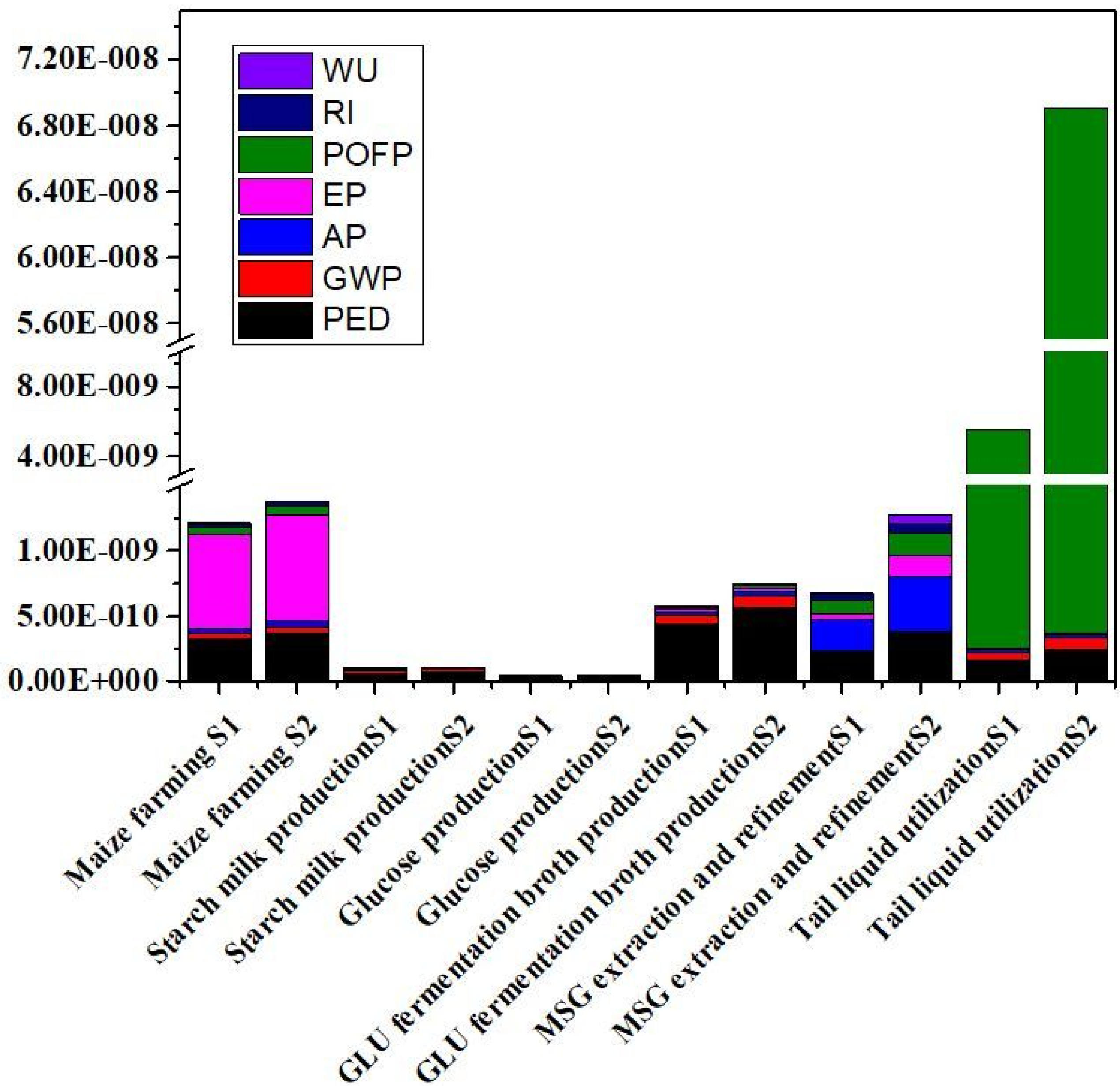

Figure 3

Normalization index of each stage in Scenario 1 and Scenario 2