Life cycle assessment on the environmental impacts of different pig manure management techniques

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Abstract: The management of livestock waste is an effective way to achieve emission reduction and carbon fixation in agriculture and rural areas. At present, aerobic composting and anaerobic fermentation are widely used in livestock waste treatment technology. In this study, pig manure management was taken as an example, a comprehensive environmental load index was constructed to quantitatively evaluate the environmental impacts of global warming, environmental acidification, eutrophication, and photochemical ozone synthesis during aerobic composting and anaerobic fermentation based on the life cycle assessment. The results showed that the potential values of aerobic composting and anaerobic fermentation were similar, and the order was global warming, environmental acidification, eutrophication, and photochemical ozone synthesis. Anaerobic fermentation contributed more to global warming, while aerobic composting contributed more to environmental acidification, eutrophication, and photochemical ozone synthesis. In addition, the environmental load index of aerobic composting was significantly higher than that of anaerobic fermentation. There were certainly regional differences in the environmental load index, and the environmental impact effect of anaerobic fermentation was low and more environmentally friendly. These findings provided a technical basis for livestock manure management in different regions of China, which was conducive to promoting animal husbandry emission reduction and carbon sequestration.

Keywords: manure management, life cycle assessment, low carbon treatment, aerobic composting, anaerobic fermentation, environmental impact assessment, emission reduction and carbon sequestration
DOI: 10.25165/j.ijabe.20221503.6212

Citation: Dong B C, Song C J, Li H B, Lin A J, Wang J C, Li W. Life cycle assessment on the environmental impacts of different pig manure management techniques. Int J Agric & Biol Eng, 2022; 15(3): 78–84.

1 Introduction

The rapid development of agriculture in China brings lots of benefits for most people, but also produces a large amount of agricultural waste, such as crop straws and livestock manure, which may cause environmental pollution if not properly treated[1]. In recent years, large-scale livestock and poultry farms rose rapidly and occupied a dominant position. China has various large-scale and standardized pig farms all over the country, the large-scale and intensive production mode did improve the efficiency of pig production greatly, but it also brought many social problems, such as manure disposal and environmental pollution. Therefore, effective treatment and efficient utilization of livestock and poultry manure is one of the important tasks for the development of livestock economic cycle in China[2]. In particular, livestock manure is one of the important sources of nitrogen and phosphorus pollution in water. Moreover, the organic matter, nitrogen and phosphorus contained in livestock manure can be used as fertilizer after proper treatment, thus reducing the use of chemical fertilizer and improving the soil texture[3]. Livestock manure can also produce biogas to realize waste recycling. Although many ways and means of utilization are available, the current utilization level and utilization rate still need to be further improved[4-8]. In China, most of the manure treatment systems are low-cost and multi-mode, mainly including septic tank, aerobic composting and anaerobic fermentation[9] At present, the domestic treatment technologies are: 1) reduction and harmless treatment, mainly including incineration, drying and deodorization; 2) comprehensive technologies, mainly including aerobic composting and anaerobic fermentation[10,11], of which aerobic composting and anaerobic fermentation are effective measures to realize waste recycling and harmless treatment of livestock manure[12,13]. Compared with other technologies, aerobic composting has the advantages of fast degradation rate, short cycle, high harmless degree and high composting efficiency. Anaerobic fermentation process does not require oxygen, thus reducing power consumption and use costs[14]. The biogas produced by anaerobic fermentation is clean energy and has good economic benefits[15]. From the perspective of reduction, harmlessness, stabilization and resource utilization, aerobic composting and anaerobic fermentation are effective treatment methods for livestock and poultry manure, which can not only effectively control the environmental pollution caused by excrement, but also realize the effect of turning waste into treasure and resource utilization. Zhao et al.[16] showed that the use of livestock manure composting improved the properties of farmland

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Received date: 2020-10-10 **Accepted date:** 2022-03-21

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soil, and compared with conventional fertilizer, the crop yield increased by 18.32%; Meng et al.[17] showed that the biochar yield increased significantly after pig manure composting, but decreased with the temperature rising.

With such problems as a large number of small and medium-sized farms in intensive farming areas, fast development, and low efficiency of waste disposal, optimization of treatment technology is the key to improving the efficiency of waste utilization. At present, many methods are available to assess the emission reduction benefits and resources recycling effects of different treatment methods, but the treatment system of livestock and poultry waste is a complex one involving environmental, social, and economic aspects, which is closely related to air, water and soil pollution, resource recycling and human health. LCA method described the complex, multi-level and potential impacts of human activities, and was helpful in technology selection[18,19]. Therefore, it is necessary to evaluate the treatment of livestock and poultry waste by using LCA method. Up to now, LCA method, as an important tool, has been applied in the study of the potential impact of bioenergy generation from agricultural wastes on different ecosystem services[20-22]. Chai et al.[23] used LCA method to analyze and assess the carbon footprint of solar greenhouse heating in winter, which showed that the carbon footprint driven by gas-fired power generation was lower than that drove by coal-fired power generation. Some studies used LCA method to analyze and assess the greenhouse gas emissions from dairy farming systems, which showed that the emission reduction measures taken for a single link might not be effective[24].

LCA method was also used to assess the potential risks and impacts[25], but there were few assessments on the treatment methods of manures. Therefore, in order to improve the treatment efficiency, and reduce the treatment cost and carbon emissions, this research monitored and evaluated the pollutant and greenhouse gas emission coefficient of aerobic composting and anaerobic fermentation combined with laboratory experiments. According to LCA method, this study evaluated low-carbon effects of different manure treatment processes, and screened for advanced low-carbon treatment technologies to provide the selection basis for comprehensive utilization methods of manure pollution.

2 Materials and methods

2.1 Data sources

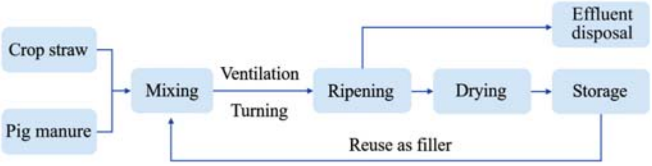
The data were obtained from China Agricultural Statistics Yearbook, China Statistics Yearbook, China Statistics Yearbook on Environment, IPCC Carbon Emission Coefficient, and China Energy Statistics Yearbook, and investigated based on the basic principles of representativeness and comprehensiveness.

2.2 Screening methods

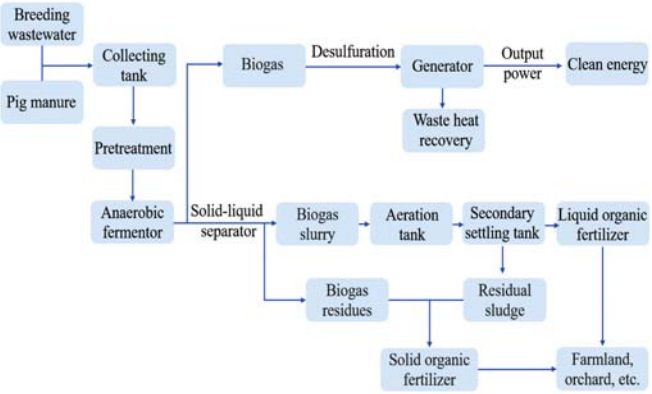
According to the international standard ISO14040 Life cycle assessment-Principles and framework[26], LCA studies were comprised of four phases: the goal and scope definition, inventory analysis, impact assessment, and interpretation. Based on the quantitative investigation and data collection for the entire life cycle of a product, LCA ran through the whole process of products, processes, and activities.

2.3 Objective and scope definition

In this study, one ton of pig manure was taken as the function unit for assessment, to analyze energy input and pollutant emission during the process of two different manure treatment methods-anaerobic fermentation and aerobic composting, and the advantages and disadvantages of the two treatment methods were compared on the basis of environmental impact. The starting boundary of the life cycle was the collection and transfer of pig manure to the treatment area. Since the processing area was in the large-scale pig farm where pig manure was collected, the manure transportation process was not included. And the ending boundary was solid waste forming mature compost products. Waste water was discharged up to standard and biogas residue and biogas slurry were utilized comprehensively. The specific research scope is shown in Figure 1.



a. Aerobic composting



b. Anaerobic fermentation

Figure 1 Research scope of the aerobic composting and anaerobic fermentation

2.4 Life cycle impact assessment

The content of impact assessment was the impact of material and energy exchange of products or processes on the external environment. In order to clarify the types of environmental impact, the results obtained from the inventory analysis were correlated with various environmental problems. According to the pollutants (CO_2, CH_4, N_2O, SO_2, etc.) released by their life cycle process to the environment, the impact types mainly include global warming, environmental acidification, eutrophication, photochemical ozone creation, and others. The impact assessment in this study was divided into four steps: 1) calculation of the potential environmental impact values, which were used to indicate the potential contribution of pollutants discharged into the environment to various types of environmental impact; 2) data normalization, indicating the extent of the total potential of environmental impact caused by the whole activity; 3) weighted assessment, which gave different weights to different types of environmental impact, and finally assessed the relative extent of potential environmental impact values; 4) calculation of the environmental impact load. The steps of the life cycle environmental impact assessment model are shown in Figure 2.

2.4.1 Data characterization

The potential value of environmental impact is calculated and expressed by Equation (1) [27]:

$$\mathrm{EP}(x)=\sum \mathrm{EP}(x)_i=\sum\left[Q(x)_i\times \mathrm{EF}(x)_i\right] \qquad (1)$$

where, $\mathrm{EP}(x)$ is the contribution of the production system to the potential impact of the xth type environmental impact; $\mathrm{EP}(x)_i$ is the contribution of the i-type emission substance to the x-type potential environmental impact. $Q(x)_i$ is the emission of the i^{th} substance;

$EF(x)_i$ is the equivalent factor of the potential impact of type i emissions on type x environmental impact.

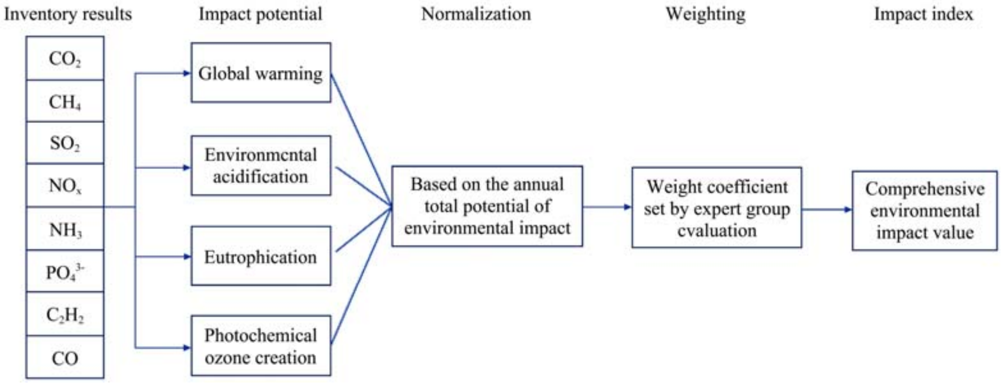


Figure 2 Life cycle environmental impact assessment model method steps

2.4.2 Data normalization

The data normalization method uses the reference value to remove the type parameter result, which is expressed by the Equation (2):

$$N_x = \mathrm{EP}(x)/S_x \tag{2}$$

where, N_x is the normalized result of the xth type of environmental impact; $EP(x)$ is the potential value of the xth type of environmental impact; S_x is the normalized reference value of the xth type of environmental impact; x is the environmental impact type. In this research, the world per capita environmental impact potential was released by Stranddorf et al.[28] in November 2005 was used as the environmental impact benchmark.

2.4.3 Weighted assessment of data

The normalized data only showed the relative extent of the potential environmental impact. However, the results of environmental pollution caused by different types of environmental impact were not all the same, and the severity was also different. Therefore, it was necessary to rank the severity of the impacts for different types of environmental impact, i.e., to give different environmental impact types their respective weights to distinguish their harm on the total environmental impact[29]. Common methods to determine the weights included the distance to target method, analytic hierarchy process, and expert assessment method.

$$\mathrm{EI}(x) = W(x) \times N(x) \tag{3}$$

where, $\mathrm{EI}(x)$ is the weighted xth type of environmental impact, $\mathrm{W}(x)$ is the weight of various types of environmental impact, and $\mathrm{N}(x)$ is the normalized result of xth type of environmental impact.

Different scholars had different research scopes and objectives, so the weight coefficients obtained for the same type of environmental impact might be different too[30]. In this study, according to the weight coefficient based on the distance to target method determined by reported studies[31], global warming (0.83), acidification (0.73), eutrophication (0.73), and photochemical ozone synthesis (0.53) were taken as the weight coefficients after normalization, and then weighted.

2.4.4 Environmental impact load

The weighted potential values of various environmental impacts were comparable, which were integrated into an index reflecting the environmental impact load (EI) on the environmental system in the whole life cycle. The formula was as follows:

$$\mathrm{EI} = \sum \mathrm{EI}(x) = \sum \left[W(x) \times N(x) \right] \tag{4}$$

where, EI is the comprehensive environmental impact value of the system; $\mathrm{EI}(x)$ is the weighted xth type of environmental impact; $W(x)$ is the weight of the xth type of environmental impact; $N(x)$ is the normalized result of the xth type of environmental impact.

2.4.5 Correction in different regions

In terms of the impact type scheme classified according to the actual situation in China by the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, environmental acidification, water eutrophication, and photochemical ozone creation are regional impacts. China has a vast territory, and the severity of environmental acidification, eutrophication, and photochemical ozone creation varies in different provinces. Therefore, when calculating the environmental impact load in different provinces, the weights of various factors are different and need to be corrected accordingly.

$$\mathrm{EImodification} = \sum \mathrm{EI}(x)\mathrm{modification} = \sum \left[W(x) \times N(x) \times I(x) \right] \tag{5}$$

where, $I(x)$ is the correction coefficient of the weight of the x-th type of environmental impact. The selection of correction coefficient is the potential value of regional environmental impact type divided by the national average potential value, and the greater the regional environmental impact type relative to the national potential value, the greater its weight.

3 Results and analysis

In this study, 1 t pig manure was taken as the function union (FU), and LCA method was adopted to assess the environmental impact of the two treatment methods of pig manure, and the environmental impact potential in the treatment process was calculated. For better analysis, the life cycle of aerobic composting was mainly divided into three stages: composting stage, turning stage and wastewater treatment stage. The life cycle of anaerobic fermentation was divided into three stages: anaerobic fermentation stage, biogas power generation stage and biogas slurry treatment stage.

3.1 Inventory analysis

The emission inventory of aerobic composting and anaerobic fermentation of pig manure referred to similar studies[31,32]. In the process of aerobic composting, the CO_2 emission was mainly from the dump turning stage and the wastewater treatment stage, and the total amount of pig manure emission per functional unit was 48.41 kg. CH_4 discharge was mainly from composting stage, turning over stage, and wastewater treatment stage. In the process of anaerobic fermentation, CO_2 emission was mainly from the fermentation stage, biogas power generation stage and biogas slurry and residue treatment stage, a total of 143.04 kg. The emission of CH_4, NO_x, CO, and SO_2 in anaerobic fermentation was mainly from the fermentation stage and the treatment stage of biogas slurry and residue. Detailed emission data are listed in

Table 1, it was seen that the amount of CO_2 released by anaerobic fermentation was larger, almost three times of aerobic composting, while the amount of CO, CH_4, NH_3, and N_2O released by aerobic composting was larger than that of anaerobic fermentation.

Table1 Life cycle pollutant emission inventory

Pollutant	Pollutant emission of aerobic composting/kg	Pollutant emission of anaerobic fermentation/kg
CO_2	48.41	143.04
CO	0.60	2.48×10^{-3}
CH_4	0.15	4.16×10^{-3}
NH_3	3.26	--
N_2O	0.02	--
NO_X	4.65×10^{-3}	0.01
SO_2	0.03	0.02

3.2 Data characterization results

Potential values of four environmental impact types, namely, global warming, eutrophication, environmental acidification, and photochemical ozone creation, were assessed by using the characterization method. The assessment results were shown in Figure 3 and Table 2. It was seen that compared with aerobic composting, anaerobic fermentation contributed more to global warming, but its contribution to environmental acidification, eutrophication, and photochemical ozone creation was significantly smaller than aerobic composting. Among the potential environmental impacts of the two treatment methods, global warming had the largest one, then followed by environmental acidification, eutrophication, and photochemical ozone creation.

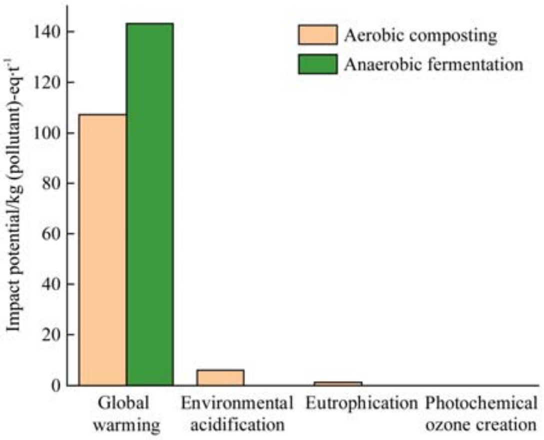


Figure 3 Aerobic composting and anaerobic fermentation process environmental impact potential

Table 2 Environmental impacts of aerobic composting and anaerobic fermentation in the life cycle

Impact type	Impact potential	
	Aerobic composting	Anaerobic fermentation
Global warming/kg CO_2-eq·t^{-1}	107.38	143.14
Environmental acidification/kg SO_2-eq·t^{-1}	6.17	0.02
Eutrophication/kg PO_4-eq·t^{-1}	1.10	1.34×10^{-3}
Photochemical ozone creation/kg C_2H_2-eq·t^{-1}	5.17×10^{-3}	0.86×10^{-3}

3.3 Data normalization and weighted assessment results

The distance-to-target method was used to determine its weight. After the weighted assessment, the comprehensive indexes of life cycle environmental impact of the two processes were 0.16 and 0.01, respectively. From Table 3, it was seen that anaerobic fermentation had a greater contribution to global warming, almost 1.33 times as much as aerobic composting. The main reason for this phenomenon was that excrement consumed CH_4 and then produced CO_2 during anaerobic fermentation. However, aerobic composting was significantly higher than anaerobic fermentation in terms of environmental acidification and eutrophication, especially eutrophication. The influencing value of photochemical ozone creation in aerobic composting was 6 times that of anaerobic fermentation. In aerobic composting, the sequence of potential influence after normalization was environmental acidification, eutrophication, global warming, and photochemical ozone creation; in anaerobic fermentation, the sequence of influence potential after normalization was global warming, photochemical ozone creation, environmental acidification, and eutrophication. At the same time, the comprehensive index of aerobic composting was significantly higher than that of anaerobic fermentation. Anaerobic fermentation had a lower impact on the environment and was more environmental-friendly. The results were consistent with those reported in similar studies (Table 4).

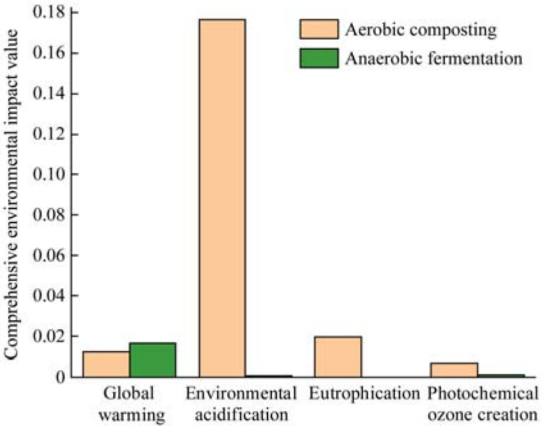


Figure 4 Aerobic composting and anaerobic fermentation process weighted assessment value

Table 3 Comprehensive environmental impact value of two kinds of treatment process

Impact type	Weight	Normalized value	
		Aerobic composting	Anaerobic fermentation
Global warming	0.83	1.23×10^{-2}	1.65×10^{-2}
environmental acidification	0.73	0.18	0.66×10^{-3}
Eutrophication	0.73	0.02	0.20×10^{-4}
Photochemical ozone creation	0.53	6.80×10^{-3}	1.13×10^{-3}
Comprehensive impact	--	0.16	0.01

Table 4 Comparison of comprehensive environmental impact values in different studies

Impact type	Normalized value		Reference
	Aerobic composting	Anaerobic fermentation	
Comprehensive impact	2.44×10^{-2}	2.16×10^{-2}	[33]
	0.16	0.01	This study

3.4 Correction results in different regions

According to the 2013 China Statistical Yearbook, the environmental acidification potential, eutrophication potential, photochemical ozone creation potential, and their correction coefficients of the waste emissions affecting environmental acidification, water eutrophication, and photochemical ozone creation in all provinces of China were obtained, as shown in Tables 5 and 6.

As the environmental impact of eutrophication, environmental acidification, and photochemical ozone creation is regional, the environmental pollution degrees and loads of the three types vary from region to region, so their weights are also different. After correction, the final comprehensive environmental impact values of the two treatment processes in each region are listed in Table 7. It was seen that the comprehensive impact value of aerobic composting in most areas was significantly greater than that of anaerobic fermentation, up to more than 30 times. Nationwide, the comprehensive impact value of aerobic composting was 10 times that of anaerobic fermentation, indicating that anaerobic fermentation was more environmental-friendly than aerobic composting.

Table 5 Discharge of major pollutants in different regions

Region	Main pollutants in exhaust gas/kg·person^{-1}		Main pollutants in wastewater/kg·person^{-1}		
	SO_2	NO_x	COD	NH_3-N	TP
National wide	15.64	17.27	17.90	1.87	0.36
Beijing	4.54	8.58	9.01	0.99	0.21
Tianjin	15.89	23.65	16.24	1.8	0.26
Hebei	18.40	24.17	18.51	1.52	0.53
Shanxi	36.05	34.45	13.2	1.58	0.22
Inner Mongolia	55.62	56.99	35.50	2.12	0.83
Liaoning	24.12	23.61	29.76	2.45	0.63
Jilin	14.67	20.94	28.63	2.05	0.57
Heilongjiang	13.41	20.36	39.09	2.42	0.62
Shanghai	9.59	16.87	10.19	1.99	0.08
Jiangsu	12.52	18.68	15.11	1.93	0.23
Zhejiang	11.43	14.77	14.35	2.05	0.19
Anhui	8.68	15.39	15.44	1.77	0.34
Fujian	9.91	12.47	17.61	2.49	0.32
Jiangxi	12.6	12.81	16.62	2.02	0.3
Shandong	18.06	17.96	19.84	1.74	0.63
Henan	13.56	17.29	14.82	1.59	0.51
Hubei	10.77	11.07	18.8	2.23	0.4
Hunan	9.71	9.15	19.03	2.43	0.36
Guangdong	7.54	12.3	17.02	2.12	0.24
Guangxi	10.77	10.64	16.67	1.76	0.29
Hainan	3.85	11.66	22.26	2.54	0.57
Chongqing	19.18	12.99	13.68	1.81	0.22
Sichuan	10.70	8.16	15.71	1.74	0.31
Guizhou	29.88	16.17	9.56	1.11	0.13
Yunnan	14.43	11.68	11.77	1.26	0.16
Tibet	1.36	14.4	8.37	1.04	0.13
Shaanxi	22.48	21.53	14.29	1.65	0.20
Gansu	22.21	18.37	15.10	1.59	0.15
Qinghai	26.84	21.99	18.10	1.71	0.10
Ningxia	62.83	70.37	35.23	2.70	0.33
Xinjiang	35.66	36.70	30.42	2.11	0.53

Table 6 Environmental impact potential and correction coefficient of major pollutants in different areas of China

Region	Environmental acidification potential /kg SO_2-eq·a^{-1}	Eutrophication potential /kg PO_4-eq·a^{-1}	Photochemical ozone creation potential /kg C_2H_4-eq·a^{-1}	Correction coefficient of environmental acidification	Eutrophication correction coefficient	Correction coefficient of photochemical ozone creation
Nationalwide	27.72	20.82	0.75	1.00	1.00	1.00
Beijing	10.54	10.38	0.22	0.38	0.50	0.29
Tianjin	32.44	27.93	0.76	1.17	1.34	1.02
Hebei	35.32	28.54	0.88	1.27	1.37	1.18
Shanxi	60.17	39.96	1.73	2.17	1.92	2.31
Inner Mongolia	95.51	66.37	2.67	3.45	3.19	3.56
Liaoning	40.65	28.59	1.16	1.47	1.37	1.54
Jilin	29.33	25.36	0.7	1.06	1.22	0.94
Heilongjiang	27.67	25.11	0.64	1.00	1.21	0.86
Shanghai	21.4	20.15	0.46	0.77	0.97	0.61
Jiangsu	25.6	22.34	0.6	0.92	1.07	0.8
Zhejiang	21.76	17.93	0.55	0.78	0.86	0.73
Anhui	19.45	18.59	0.42	0.7	0.89	0.55
Fujian	18.63	15.63	0.48	0.67	0.75	0.63
Jiangxi	21.57	15.8	0.61	0.78	0.76	0.81
Shandong	30.63	21.68	0.87	1.1	1.04	1.15
Henan	25.66	20.71	0.65	0.93	0.99	0.87
Hubei	18.52	14.01	0.52	0.67	0.67	0.69
Hunan	16.12	11.9	0.47	0.58	0.57	0.62
Guangdong	16.16	15.25	0.36	0.58	0.73	0.48
Guangxi	18.22	13.24	0.52	0.66	0.64	0.69
Hainan	12.01	14.94	0.18	0.43	0.72	0.25
Chongqing	28.27	15.82	0.92	1.02	0.76	1.23
Sichuan	16.42	10.41	0.51	0.59	0.5	0.68
Guizhou	41.20	19.00	1.43	1.49	0.91	1.91
Yunnan	22.61	14.05	0.69	0.82	0.67	0.92
Tibet	11.44	16.94	0.07	0.41	0.81	0.09
Shaanxi	37.55	25.41	1.08	1.35	1.22	1.44
Gansu	35.07	21.81	1.07	1.26	1.05	1.42
Qinghai	42.24	26.00	1.29	1.52	1.25	1.72
Ningxia	112.09	81.54	3.02	4.04	3.92	4.02
Beijing	61.35	43.22	1.71	2.21	2.08	2.28

Table 7 Comprehensive environmental impact values of two treatment processes in different regions

Region	Comprehensive influence	
	Aerobic composting	Anaerobic fermentation
Nationalwide	0.15698	0.01475
Beijing	0.06740	0.01402
Tianjin	0.18383	0.01485
Hebei	0.19771	0.01499
Shanxi	0.32556	0.01611
Inner Mongolia	0.51313	0.01749
Liaoning	0.22476	0.01530
Jilin	0.16765	0.01474
Heilongjiang	0.15950	0.01467
Shanghai	0.12553	0.01440
Jiangsu	0.14697	0.01459
Zhejiang	0.12567	0.01448
Anhui	0.11515	0.01433
Fujian	0.10956	0.01436
Jiangxi	0.12452	0.01453
Shandong	0.17097	0.01489
Henan	0.14735	0.01464
Hubei	0.10863	0.01440
Hunan	0.09535	0.01431
Guangdong	0.09715	0.01423
Guangxi	0.10691	0.01439
Hainan	0.15698	0.01402
Chongqing	0.06740	0.01489
Sichuan	0.18383	0.01435
Guizhou	0.19771	0.01553
Yunnan	0.32556	0.01461
Tibet	0.51313	0.01392
Shaanxi	0.22476	0.01518
Gansu	0.16765	0.01513
Qinghai	0.15950	0.01543
Ningxia	0.12553	0.01806
Xinjiang	0.14697	0.01611

4 Conclusions

By using the LCA system to assess the environmental impact of the two manure treatment methods, the following conclusions were drawn: 1) the comprehensive index of the life cycle environmental impact of aerobic composting and anaerobic fermentation was 0.16 and 0.01, respectively. It was concluded that for the treatment of livestock manure, anaerobic fermentation was more environmental-friendly; 2) among the normalized potential impact values in aerobic composting, environmental acidification had the largest potential impact value, followed by eutrophication, global warming, and photochemical ozone creation; after normalization of the anaerobic fermentation process, global warming had the greatest potential impact, then followed by photochemical ozone creation, environmental acidification, and eutrophication; 3) by revising the weight coefficient of regional environmental impact types in different regions, it was concluded that the comprehensive environmental impact values of the two treatment processes were different in various regions, and the treatment methods of livestock manure should be differentiated according to different regions.

Acknowledgements

This work was financially supported by the Public Welfare Industry (Agriculture) Research Funding Project (Grant No. 201303091).

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