Comparison of life cycle assessment of large-scale biogas projects with different raw materials in China

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Abstract: The anaerobic digestion (AD) disposal of stover and cattle manure is of great significance to the development of low-carbon economy and green energy in China, but it will also have an impact on the environment, and the degree of influence is different for various raw materials. In this study, life cycle assessment (LCA) methods were applied to analyze and compare the impact of corn stovers biogas projects (CSBP) and dairy manure biogas projects (DMBP) on the environment during the whole operation stage. The results of inventory analysis were evaluated by ReCiPe2016 Hierarchy(H) mid-point (problem-oriented) and end-point (destruction-oriented) method, respectively. The results showed that the net energy efficiency of CSBP was higher (763.903 kW·h/FU) and the greenhouse gas (GHG) emission reduction of DMBP was more (5541.418 kg CO_2-eq/FU). The anaerobic digestion (AD) units have the greatest environmental impacts, and human carcinogenic toxicity is the largest environmental impact category (1.16-1.43 PE). The key to reducing environmental impact is reducing the input of chemical substances and the waste of electric energy. Both CSBP and DMBP have a favorable impact on ecosystem quality and resources, and CSBP is more beneficial to the environment (–10.297 Pt). Co-digestion is an important measure to reduce the environmental damage from biogas projects. These research results provide theoretical support for the selection of raw materials for large-scale biogas projects in China, provide technical basis for reducing the impact of actual operation on the environment, and promote the resource utilization of agricultural waste and carbon dioxide emission reduction and sequestration.

Keywords: life cycle assessment, environmental impact assessment, large-scale biogas projects, bioenergy, carbon dioxide emission reduction

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1 Introduction

China is a major agricultural nation, which not only has abundant agricultural resources but also generates substantial amounts of agricultural wastes[1]. As the largest biomass resource, crop stover has the characteristics of being diverse, large in quantity, and easy to obtain at a low cost. According to statistics, China can collect more than 7×10^8 t of stover every year, and the comprehensive utilization of stover is about 6.47×10^8 t[2]. As a by-product of agricultural production, cow dung is also a huge biomass resource. However, its energy value is diminished because of the low levels of organic matter and the high concentrations of ammonia[3]. Improper disposal of a large number of agricultural wastes will produce a plethora of gaseous pollutants, including CO_2, CO, NO_x, particulate matter and harmful organic waste gas, which will cause harm to the rural environment[4]. Nevertheless, agricultural waste, through certain measures and technological treatments, can be effectively utilized for resource recovery, energy generation, and high-value applications[5].

In recent years, significant breakthroughs have been made in the key technologies for producing biogas from the corn stovers (CS) and the dairy manure (DM), and large-scale centralized supply projects for stover biogas have gradually increased[6]. As a new renewable energy, biogas has received widespread attention at home and abroad. Its development and utilization are an important way to alleviate energy pressure and protect the ecological environment[7]. Large scale biogas projects can achieve a harmless and energy-efficient treatment of agricultural waste. The biomethane produced can be converted into electricity energy and incorporated into the power grid or directly integrated into biological natural gas

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transmission pipelines after treatment, reducing the consumption of fossil energy. The generated biogas fertilizer can also partially replace fertilizers[8]. It not only effectively improves the comprehensive utilization level of agricultural wastes in the region, but also improves the local energy consumption structure[9].

Currently, there are many methods to assess the emission reduction benefits and resource recycling effects of different treatments, but the anaerobic digestion system for agricultural waste is a complex system that involves the environmental, social, and economic aspects, and is also related to the air, water, and soil pollution, resource recycling, and human health[7]. Life Cycle Assessment (LCA) is a widespread methodology that synthesizes the whole inputs, outputs and potentially comprehensive environmental impacts of the products over its entire life cycle, and can fully reveal the environmental burden of different activities[10,11]. Recently, numerous scholars have employed the LCA method to investigate the influence of different biomass utilization systems on the environment. Soam et al.[12] discovered that stover biogas power generation has a favorable environmental impact through LCA method. Jury et al.[13] conducted sensitivity analysis on the process of stover AD to produce biogas using the LCA method and found that the most sensitive indicator to the environmental impact is biogas production. Poeschl et al.[14] conducted an environmental impact LCA on different forms of biomass material utilization and found that the use of stover had better outcomes in the environmental impact. Some scholars have also conducted research on the life cycle process of the fecal biogas production. Mezzullo et al.[15] analyzed the small and medium-sized Dairy Manure Biogas Project (DMBP) with the LCA method, and the research indicated that the production and use of biogas are beneficial in reducing environmental damage. Lansche and Müller[16] analyzed the replacement of DM combustion with biogas systems in rural Ethiopia through the LCA method in terms of environmental impact. The study showed that replacing DM combustion with biogas systems had a small impact on the environment. The research by Whiting shows that different forms of energy conversion, such as power generation or heat generation, can significantly reduce the impact on the environment and obtain clean energy through the AD of agricultural waste[17]. Large and medium-sized stover biogas projects and stover pyrolysis gasification projects is essential for energy substitution, reducing greenhouse gas (GHG) emissions, reducing non-point source pollution caused by stover incineration and waste, and protecting the environment[18]. There are also studies that analyze and assess GHG emissions from dairy farming systems using the LCA methodology, and the results show that the emission reduction measures targeting a single segment may not be effective[19].

In summary, current researches have mostly focused on a single special case of LCA, and there are relatively little comparative researches on the environmental benefits caused by biogas engineering using two different raw materials: CS and DM. There are also little literatures on the specific impact of each unit in biogas engineering on the environment, and optimizing the operation of biogas engineering based on the quantitative results. Even some studies have shown that large and medium-sized biogas projects do not bring good environmental benefits, and the ways to improve treatment efficiency and reduce treatment costs and carbon emissions still need further research[20]. In addition, for the LCA of biogas engineering, most of it is currently based on literature and database information, and there are very few cases that combine the actual engineering[21]. This study will also serve as a reference for the establishment of the localized LCA inventory database in China, and provide theoretical support for selecting raw materials for biogas engineering.

Therefore, this study used the LCA method to analyze and compare the environmental impact of CS and DM biogas projects during their operation, based on the actual large-scale biogas projects in northern China. The quantitative analysis of environmental impact of each unit was conducted based on the energy analysis, GHG emission reduction, and mid-point environmental impact categories, and measures to reduce the environmental effects of biogas engineering were proposed. Ultimately, the type of damage was used as a guide to identify more sustainable and suitable fermentation feedstocks for biogas projects, which will provide a basis for a comprehensive approach to the utilization of agricultural wastes.

2 Materials and methods

2.1 Description of large-scale biogas engineering

This study took two large-scale biogas power generation projects of an energy company in northern China (47°10′59″N, 124°52′09″E and 45°42′18″N, 125°15′55″E) as an example to conduct the empirical analysis. The two biogas projects use CS and DM as the raw materials for AD to produce biogas for power generation, and are then integrated into the national power grid. The project schematic is shown in Figure 1.

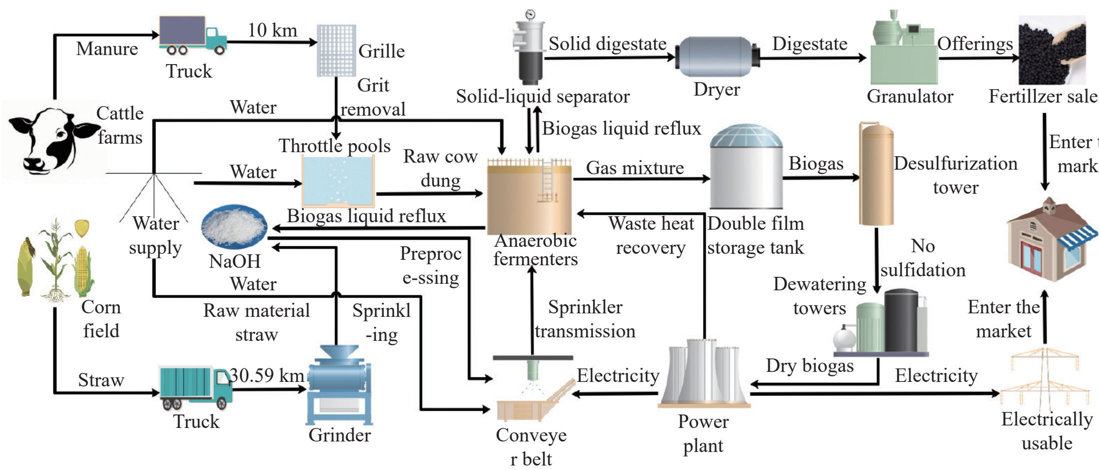


Figure 1 Large scale-biogas project schematic diagram

2.1.1 CSBP

The single digestion tank of this biogas project has a height of 18 m, a diameter of 20 m, a volume of 5652 m^3, an average annual CS treatment capacity of about 50 000 t, an annual biogas production of about 1.16×10^9 m^3, and an annual power generation of about 2.088×10^9 kW·h. There are pre-treatment units, AD units, biogas purification units, biogas slurry treatment units, and power generation units constructed. Due to the dense lignocellulosic structure of CS, efficient pre-treatment is required before AD[22]. The CS is crushed to a particle size of 3-5 cm, and after NaOH pre-treatment, it is pumped into the digestion tank. The AD process adopts medium temperature (38±1)°C wet fermentation. During the AD process, the biogas slurry and residue are separated by solid and liquid, and then partially refluxed to the digestion tank to supplement the number of microorganisms, improve AD efficiency, and save water consumption. The biogas slurry is dried and granulated to produce organic fertilizer by-products. The biogas produced by AD is removed from the hydrogen sulfide and water in the biogas through the wet desulfurization and steam water separation, and enters the power generation units for power generation. The waste heat of the power generation units is used for heating and insulation of the digestion tank.

2.1.2 DMBP

The DM of this DMBP comes from cooperative cattle farms in surrounding villages and towns, with an annual collection capacity of about 2×10^5 t, an annual biogas production of about 1.224×10^9 t, and an annual power generation of about 2.387×10^9 kW·h. The processing unit is similar to the CS biogas project. Due to the presence of a certain number of stones and sand in DM, a grid multi-stage sand removal process is used to remove the impurities. The impurities are spiral fed into a regulating tank for heating and homogenization, and then pumped into a digestion tank for AD. The AD process is medium temperature (38±1)°C wet fermentation. The biogas produced by AD undergoes wet desulfurization and drying before generating electricity. The waste heat from the generator set is used for heating and insulation of the digestion tank. After solid-liquid separation, the biogas slurry from the AD process partially flows back to the digestion tank to regulate the concentration of the AD system, and the biogas slurry is made into solid fertilizer.

2.2 LCA

The LCA in this study follows the standards of ISO 14 040 and 14 044 to develop the evaluation framework[11]. The LCA includes the next four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation, all of which are interrelated[19]. The basic data of this study comes from on-site research and technical reports (main data) provided by biogas engineering parties, as well as academic literature and research data of similar biogas engineering projects in China (secondary data), and is supplemented by the Ecoinvent 3 database. This study used SimaPro 9.0 software (PRé Sustainability, Netherlands) to model the entire lifecycle assessment and characterized the environmental impact using the ReCiPe2016 Hierarchy (H) method[23].

2.2.1 Goal and Scope Definition

The primary purpose of this study is to evaluate and compare the environmental impact of AD of different raw materials (CS and DM), representing two large-scale biogas projects, and to identify the most sustainable solutions by quantifying the environmental burdens related to each scenario through LCA. According to the characteristics of each process flow in biogas engineering, the life cycle start boundary is defined as the transportation of fermentation raw materials to the biogas engineering, and the ending boundary is the power generation of biogas after purification. The specific boundary division of the life cycle is illustrated in Figure 2, and the energy flow within the system boundary is described as follows:

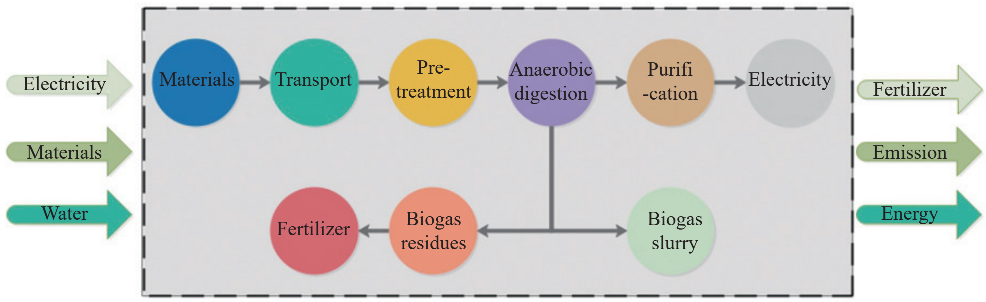


Figure 2 The system boundary of life-cycle assessment in biogas power generation process

1) CS is a by-product produced during the crop cultivation, while DM is the waste excreted by animals. Therefore, the growth process of CS and the production process of DM are considered to have no impact on the environment.

2) There are many types of materials required for engineering infrastructure, and significant differences in building materials among different projects. The emissions generated during the construction phase account for a high proportion of the overall emissions of the system, and the uncertainty of the final evaluation results is significant. Therefore, the infrastructure construction, equipment maintenance, and transportation of the factory are not included in the system.

3) The entire system has no gas leakage during AD, biogas purification, and power generation processes, without causing any impact on the environment.

4) After transportation, it is assumed that CS and DM are placed in covered storage tanks at room temperature to prevent emissions during the storage and to avoid possible hydrolysis processes.

5) Ignoring the labor force of the entire system, the emissions and energy consumption of people throughout the entire LCA process are zero.

6) The proposed operation life of the two biogas projects is 25 years, and the impact on the environment is not taken into account when the facilities are demolished[24].

2.2.2 Functional unit

Functional unit (FU) is the reference units related to all inputs, outputs, and environmental impacts, expressing the functionality of the system being analyzed, and different FU can be used according to the scope of LCA[25]. Due to the fact that the main function of biogas engineering is to treat solid waste and produce renewable electricity, the FU of this study is 1 MW·h of electricity input into the State Grid of China, which is consistent with previous research on biogas engineering[26,27].

2.2.3 LCA inventory analysis

LCA inventory analysis refers to the summary of all substances and energy input and output streams within the boundaries of the LCA system, including the summary of substances and energy consumed in the process, useful substances and energy recovered, and pollutants discharged in the entire process, waste water and waste residue, while objectively quantifying all data based on functional units. It is a pivotal aspect of LCA research, and if the data is not accurate enough, it will seriously affect the evaluation results[21]. Therefore, the collected data is only used after multiple inspections, verifications, and evaluations to ensure the accuracy of the results. The input and output inventory data of this study were listed in Table 1 and the system is divided into 5 units. The data collected through inventory analysis is based on the average annual input/output of biogas engineering, and converted based on FU (power generation of 1 MW·h). In addition, as the final output product of biogas engineering, electricity is based on the actual grid connected electricity of the biogas engineering, fully considering the conversion efficiency of the power generation process.

Table 1 LCA inventory of biogas power generation process

Unit process	Parameters	CS	DM	Unit	I/O
Transport	Transport	67.438	83.794	t·km	I
Pre-treatment	CS crush	11.574	-	kW·h	I
	NaOH	0.040	-	t	I
	Electricity-PT	13.911	68.795	kW·h	I
Anaerobic digestion	RS	2.204	-	t	I
	CM	-	8.379	t	I
	Water	5.511	4.190	t	I
	Electricity-AD	75.816	261.187	kW·h	I
	Urea	1.066	-	t	I
	Biogas	555.556	554.327	m^3	I
Biogas purification	Electricity-BP	36.420	70.303	kW·h	I
	Desulfurizer (Na_2CO_3)	0.062	0.103	t	I
Residue disposal	Electricity-RD	28.109	142.283	kW·h	I
	Fertilizer	0.551	2.908	t	O
Products	Electricity-PR	1000.000	1000.000	kW·h	O

1) Transport units: The transportation radius of CS refers to the improved model of CS collection and transportation. It is calculated that the transportation radius of CS in this study is 30.59 km. The calculation formula and parameters are shown in Equation (1).

$$R=\left(\frac{M}{\rho f_1 f_2 f_3 \pi}\right)^{\frac{1}{2}} \tag{1}$$

where, R expresses the CS transportation radius, km; M expresses the annual CS consumption (50 000 t); ρ expresses the CS yield per unit cultivated area (486.23 kg/hm^2); f_1 expresses the proportion of arable land area to the national land area of 14.2%; f_2 expresses the CS collection coefficient of 0.73; f_3 expresses the CS collection strength of 0.35.

DM comes from the cattle farms around the project, with a transportation radius of 10 km. The raw materials are transported to the biogas plant by a diesel truck that has a load capacity of 20 t, and the average fuel consumption of the truck is 0.08 L/(t·km)[28]. The basic parameters of the physicochemical properties of CS and DM are derived from the annual average statistics of biogas engineering, and their specific values are listed in Table 2.

Table 2 Physicochemical properties of fermentation raw materials for biogas engineering

Parameter	CS	DM
TS/%	91.375±2.218	19.931±0.831
VS/%	83.251±3.412	16.568±0.251
C/%	46.061±2.358	41.612±1.852
H/%	5.46±0.177	5.651±0.215
N/%	0.767±0.051	1.656±0.081
S/%	0.152±0.015	0.312±0.015
Cellulose/%	32.121±0.614	24.135±1.182
Hemicellulose/%	24.325±1.015	22.112±1.256
Lignin/%	6.128±0.537	8.365±0.521

2) Pre-treatment units: Biogas engineering using CS as raw material adopts a combination of physical and chemical pretreatment methods. The CS is first mechanically cut, crushed, and rubbed. Subsequently, a mixture of 2% NaOH and refluxed biogas slurry was used to spray and mix the CS evenly, in order to fully destroy the structure of lignocellulose.

During the pre-treatment of DM, it first passes through a grid for sand and sediment removal, and then enters a homogenization tank for pre-heating and homogenization of the material. The raw materials before and after pre-treatment do not consider quality loss, and the pre-treatment process defaults to not producing polluting gases such as dust and exhaust gas. At present, the main source of electricity in China is thermal power generation, and the electricity used in this study's preprocessing is from the State Grid of China (10 kV, 50 Hz).

3) AD units: The pretreated raw materials are pumped into the AD tank by a feed pump, and corresponding quality urea is added to the digestion tank according to the optimal carbon to nitrogen ratio (25:1) of AD[29]. The C/N of fresh DM is 25.13, which is close to the optimal carbon to nitrogen ratio, so urea is not added. The two biogas projects in this study both adopt the medium temperature AD, and the fermentation temperature is maintained at (38±1)°C based on the waste heat generated by biogas power generation; using wet fermentation with a total solid concentration of about 10%, combined with the amount of biogas slurry reflux, 2.5 t of water need to be added to 1 ton of CS, and 0.5 t of water need to be added to 1 t of DM[27]. To prevent the scum from crusting in the AD system, biogas engineering often uses intermittent mechanical stirring, and the energy consumed is uniformly represented by electrical energy. The biogas produced by CS AD includes CH_4 (60.08%), CO_2 (35.15%), H_2O (2.51%), N_2 (1.53%), and H_2S (<2.25 mg/L). In addition, the biogas produced by DM AD includes CH_4 (64.98%), CO_2 (32.50%), H_2O (1.98%), and H_2S (<3.0 mg/L). The biogas used in biogas engineering is stored in a 1700 m^3 double membrane storage tank.

4) Biogas purification units: The desulfurization process of the biogas engineering in this study adopts the wet desulfurization method, with the desulfurization agent Na_2CO_3. In addition, the desulfurization catalyst is considered not to be consumed. The H_2S concentration of the desulfurized biogas is lower than 7.5 mg/L. Due to the large amount of water carried in by the biogas after wet desulfurization, it needs to go through a dehydration device for steam water separation. During the process of biogas purification, the amount of methane is considered unchanged[30].

5) Waste disposal units: This unit mainly deals with the treatment process of biogas slurry. After AD, the digestive slurry undergoes solid-liquid separation, where the biogas slurry is pumped back to the digestion tank and pre-treatment room. The

biogas slurry is preheated and dried by biogas power generation, and then granulated into organic fertilizer. This study does not take into account the environmental emissions of organic fertilizers during sales and transportation, and only serves as the final by-product.

2.2.4 Life cycle assessment of impact

The ReCiPe2016 method is one of the most broadly utilized methods in the field of LCA studies, with selected feature factors at the mid-point level due to their strong correlation with environmental flow and relatively low uncertainty[31]. This method combines the advantages of the mid-point and the end-point method, using the mid-point method to quantify the results and trace the original emissions to identify specific environmental issues and their impact mechanisms, and then using the end-point method to evaluate the final damage caused by emissions and the entire consumption process. Its intuitive results are more conducive to environmental decision-making[32]. Based on the life cycle inventory analysis, this study evaluated 18 mid-point and 3 end-point impact indicators (Table 3). These impact indicators include most of the environmental impact indicators that have attracted international attention over the last 5 years. In the impact assessment, each type of environmental impact is converted to the same characteristic pollutant according to the equivalent method. Then, according to the standardization factor after the standardization weight, eliminate the dimension difference of different impact types, get the standard equivalent environmental impact potential size, intuitive evaluation and analysis[24].

Table 3 Environmental impact types and characteristic units based on the Recipe 2016 mid-point method

Environmental impact category	Characteristic unit	Standardization factor
Climate change	kg CO_2-eq	1.72×10^{-4}
Fossil resource scarcity	kg oil-eq	1.02×10^{-3}
Human carcinogenic toxicity	kg 1,4-DB-eq	3.39×10^{-3}
Human non-carcinogenic toxicity	kg 1,4-DB-eq	4.50×10^{-7}
Marine ecotoxicity	kg 1,4-DB-eq	4.06×10^{-7}
Fine particulate matter formation	kg PM2.5-eq	3.91×10^{-2}
Water consumption	m^3	3.75×10^{-3}
Freshwater ecotoxicity	kg 1,4 DB-eq	3.44×10^{-3}
Freshwater eutrophication	kg P-eq	1.54
Ionizing radiation	kBq Co-60 eq to air	1.43×10^{-3}
Land use	Annual crop eq·y	1.62×10^{-4}
Marine eutrophication	kg N-eq	0.22
Mineral resource scarcity	kg Cu-eq	8.33×10^{-6}
Ozone formation, Terrestrial ecosystems	kg NO_x-eq	5.63×10^{-2}
Ozone formation, Human health	kg NO_x-eq	4.86×10^{-2}
Stratospheric ozone depletion	kg CFC-11-eq	14.21
Terrestrial acidification	kg SO_2-eq	2.44×10^{-2}
Terrestrial ecotoxicity	kg 1,4-DB-eq	6.11×10^{-5}

3 Results and discussion

3.1 Analysis of life cycle energy and GHG emissions

The energy input mainly refers to the total energy input during the operation phase of CSBP and DMBP, including the input of electrical energy and the energy of diesel during the transportation phase[33]. Among them, the energy content of diesel is 46 900 kJ/kg [34]. In addition, the energy output is based on the FU of this study, which is uniformly 1 MW·h. The results of the life cycle energy analysis of the biogas project are shown in Figure 3a. Overall, the energy input of DMBP (629.896 kW·h/FU) is 2.668 times that of CS. The higher energy input mainly comes from the AD process, because DM has high humidity and viscosity, and the fiber structure of CS is relatively loose. Therefore, DMBP requires stronger stirring equipment and more energy input to achieve effective mixing and reaction. In addition, due to the high moisture content of DM, its unit mass biogas production is significantly lower than that of CS. As a result, more DM is needed per FU of electricity produced. Therefore, the energy input of DMBP is higher, which can also be seen in the biogas purification and biogas slurry separation units. Overall, CSBP has the highest net energy balance (763.903 kW·h/FU), indicating that its economy is higher than DMBP[35]. The key to improving the economic efficiency of biogas engineering lies in reducing the stirring power consumption of the AD process. The stirring power consumption of biogas engineering in this study accounts for 30% to 40% of the total energy input, similar to the results of Kress et al.[36], who reported that the stirring power consumption accounts for about 50% of the total electricity consumption of biogas plants. Compared to other types of biomass (stover) disposal scenarios, Alengebawy et al.[24] reported the highest net energy in the briquette fuel scenario (3087.5 kW·h/FU), followed by the biogas scenario (987.7 kW·h/FU) and syngas (629.4 kW·h/FU), which is similar to the results of this study. The reason why briquette fuel has a higher net energy balance is the downstream processing of briquette fuel involved only electricity for drying and briquetting. While for biogas and syngas systems, stirring electricity, heating the reactor, and steam were all included. Therefore, it broadens a new direction for the resource utilization of agricultural waste.

Optimizing the energy flow of biogas engineering is conducive to improving its economy. The current measures to improve the net energy efficiency of biogas engineering are mainly to improve the efficiency of electric energy utilization and reduce unnecessary energy loss. At the same time, optimizing the digestion process, selecting the right raw materials, adding auxiliary materials, optimizing the biogas collection system, recycling waste heat, biofilm reactor technology, and gas purification technology are also hot topics of current attention[1-4].

Normalize different GHG using CO_2 equivalence factors and use kg CO_2-eq to represent GHG emissions. The emission factors are based on the GWP20, GWP100, and GWP500 methods recommended by IPCC[37], and their normalization coefficients are listed in Table 4. It also summarizes the pollutant emission factors of substances and energy within the biogas engineering system. Throughout the process, the GHG emissions from the CSBP were 573.547 (GWP20), 557.386 (GWP100), and 518.847 kg of CO_2-eq/FU (GWP500), indicating that their impact on GHG emissions has weakened over time. This may be due to some GHG (such as N_2O) undergoing secondary reactions in the air and converting them into other GHG or non-GHG[38]. As is well known, the CO_2-eq generated by direct combustion of CS is higher than 1500 kg/t[28], so the preparation of biogas from CS has obvious advantages in reducing GHG emissions. The GHG emissions from the DMBP are 733.724 (GWP20), 814.328 (GWP100), and 777.586 CO_2-eq/FU (GWP500), and their variation over the time is opposite to that of the CSBP (Figure 3b-3d, respective). This is because the DM biogas project has invested a large amount of electricity during operation, emitting a large amount of CO_2 and CH_4. However, CH_4 has a greater impact on GHG, and its impact will increase over the time. Therefore, using agricultural waste for biogas power generation has a good potential to reduce GHG emissions.

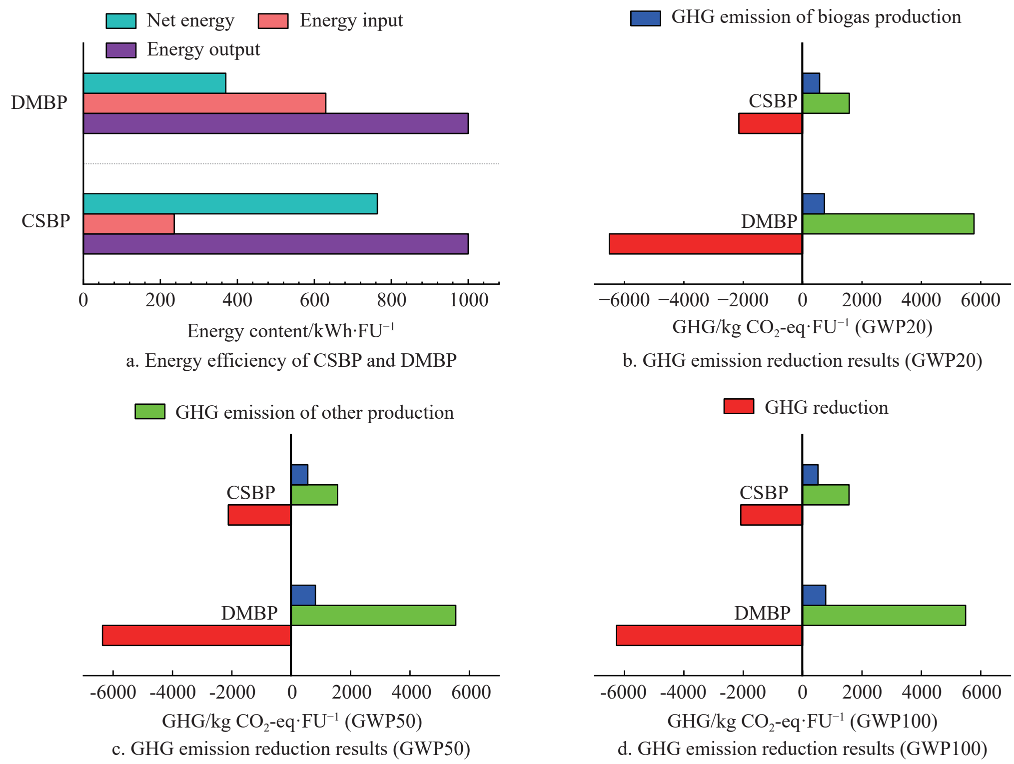


Figure 3 Energy efficiency (a) and GHG emission reduction results (b-d) of CSBP and DMBP

Table 4 Emission factors for input and output parameters used in LCA inventory (kg substance/unit)

Parameters	CO_2	CH_4	N_2O	References
Electricity/kW·h	1.077	1.067×10^{-5}	0.16×10^{-3}	Xing et al.[45] (2010)
Biogas/m³	0.214		0.31×10^{-3}	Wang et al.[46] (2010)
Nitrogen fertilizer/kg	2.070	1.61×10^{-3}		
Phosphate fertilizer/kg	1.120	1.86×10^{-3}		Wang et al.[28] (2017)
Potash fertilizer/kg	0.625	1.56×10^{-3}		
GWP20/kg CO_2-eq	1	56	280	
GWP100/kg CO_2-eq	1	21	310	Williams et al.[47] (2010)
GWP500/kg CO_2-eq	1	6.500	170	
NaOH/kg	1.200	1.7×10^{-8}	0.21×10^{-3}	Kumar et al.[48] (2012)
Urea/kg	1.705	9.67×10^{-3}		Duval-
Na_2CO_3/kg	0.684	1.3×10^{-8}	0.15×10^{-3}	Dachary et al.[49] (2023)
Diesel/L	3.160	1.51×10^{-4}	2.11×10^{-4}	Piringer et al.[50] (2006)

Biogas engineering has the characteristics of sustainability and environmental protection. The carbon reduction of biogas engineering in this study is based on the substitution of coal-fired power generation (1126.824 CO_2-eq/FU) by biogas engineering power generation and the substitution effect of by-product organic fertilizers on traditional chemical fertilizers. In this case, the emission reductions from replacing chemical fertilizers with organic fertilizers were taken into account in the calculation of life cycle carbon emission reductions. The proportion of chemical fertilizer use per unit area in China is nitrogen fertilizer (72.23%), phosphorus fertilizer (19.56%), and potassium fertilizer (8.21%)[39]. In addition, the best fertilization model for black soil farms in Northeast China is the proportion of organic fertilizer replacing traditional chemical fertilizers at 30%[40]. From Figure 3c, it was observed that the carbon reduction values of biogas engineering are 1561.401 and 5541.418 CO_2-eq/FU(GWP100), respectively. The carbon reduction effect of DMBP is significantly higher than that of CSBP, with a reduction ratio of up to 3.55 times.

The high potential for carbon reduction comes from the substitution of fertilizers. In addition, research has indicated that the implementation of organic fertilizers in soil produces less GHG emissions because AD both decreases the organic matter content of the substrate and reduces the volatilization of NH_3[41]. Although single digestion of DM is more beneficial to the environment than CS, it is suggested that DM should be digested with other substrates to improve the economic efficiency of DMBP[25,42]. Furthermore, Styles et al.[43] used DM combined with food waste to produce the biogas and found that co-substrate can reduce GHG emissions. In addition, the waste heat from electricity generation in this study is also reused in pre-treatment and AD units to replace the heat generated by coal-fired power generation, further reducing the emissions[44]. Different benchmark methods for GHG emission reduction will affect the emission reduction value. Relevant studies calculated that the emission reduction of biogas project is 1637 CO_2-eq/FU based on the replacement of rice straw open-air burning[24], which is different from the results of this study. The reason may be that the selected emission reduction methods are different, and the difference of FU will also affect the difference of emission reduction.

3.2 Analysis of environmental impact indicators at mid-point in the life cycle

This study evaluated 18 mid-point impact categories, and the results comparing with CSBP and DMBP are shown in Figure 4. It presented the impact level of each environmental impact category with the maximum value (100%) of this two-biogas project as a reference[51].

Throughout the entire lifecycle, CSBP contributes more to the seven mid-point impact categories of marine ecotoxicity, water consumption, freshwater ecotoxicity, ionizing radiation, marine eutrophication, mineral resource scarcity, and terrestrial ecotoxicity than DMBP. Marine ecotoxicity is an indication used to evaluate the impact of discharges of hazardous constituents on marine ecosystems, mainly influenced by chemical substances[52]. The CSBP requires a large amount of NaOH pretreatment to increase biogas yield, but the production of NaOH requires a large quantities of seawater electrolysis energy, which can cause damage to marine ecosystems. Like the marine ecotoxicity, freshwater and terrestrial ecosystems are equally affected by toxicity. Due to the use and production of chemicals such as solvents, reactants, and ammonia during the urea production process, they may contaminate water bodies and have toxic effects on aquatic organisms.

In addition, the toxin value of DMBP is not lower than a very high value, only 80% to 85%, which may be caused by the accumulation of heavy metals and other chemical contaminants[53]. The accumulation of heavy metals in CS come directly from the plant growth process, which are generally relatively low. In contrast, the heavy metals in DM originate from feed. Due to the high density and intensification of farming, the accumulation of heavy metals in cattle manure is relatively significant, leading to the pollution of the surrounding environment[54]. In the analysis of the water consumption index, the value of CSBP is 1.96 times that of DMBP (Figure 4c). The analysis shows that CS requires a great deal of water resources in AD process due to its low water content, so its impact on this index is relatively high. To reduce the consumption of water resources, some biogas projects adopt dry process, but the corresponding stirring power consumption increases exponentially, consuming a large amount of electrical energy. This will result in an addition to marine ecotoxicity, as the marine ecosystems have a strong sensitivity to electricity[55]. Eutrophication is considered to be a phenomenon where excessive levels of nutrients (such as N and P) in water bodies cause excessive growth and reproduction of aquatic organisms, leading to water pollution[56]. The major cause of eutrophication of water bodies caused by biogas projects is the discharge of wastewater and biogas slurry. The wastewater generated during the urea production process contains high concentrations of nitrogen compounds, and the anaerobic digested biogas slurry after solid-liquid separation also poses a risk of eutrophication if it is not properly treated[23].

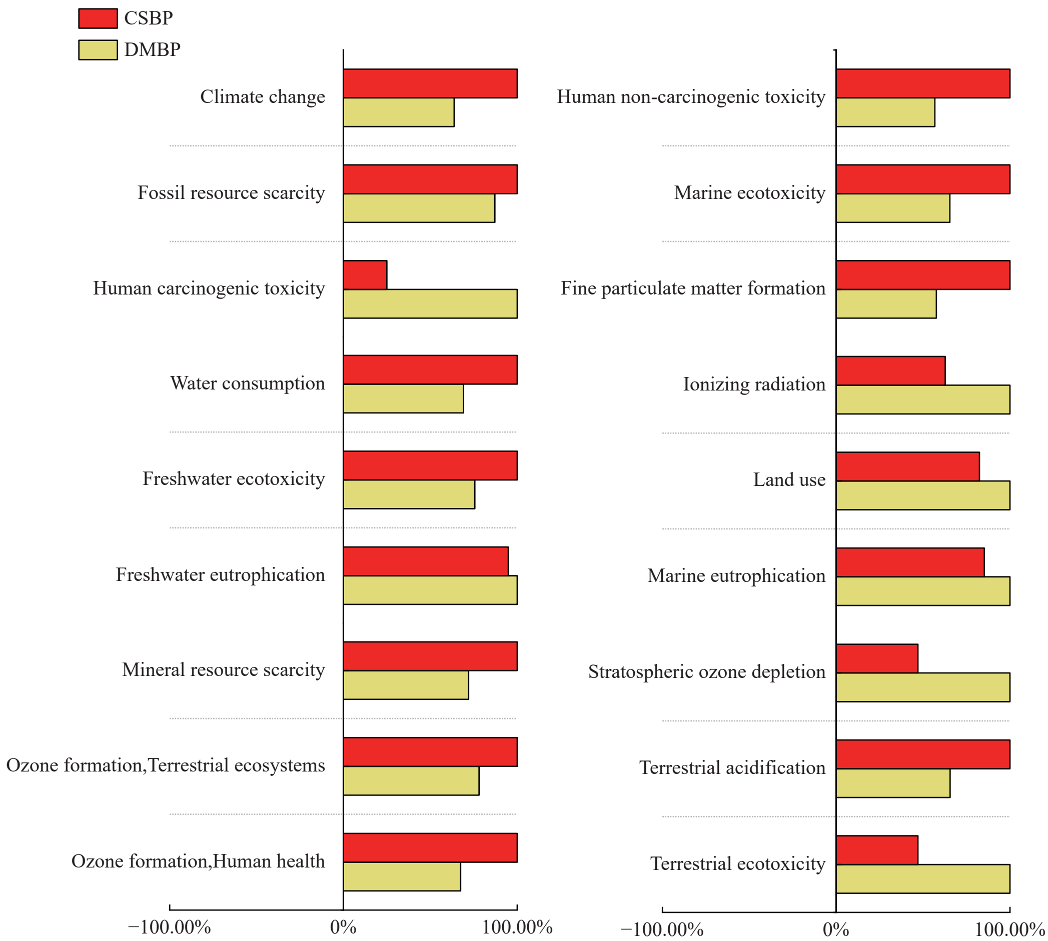
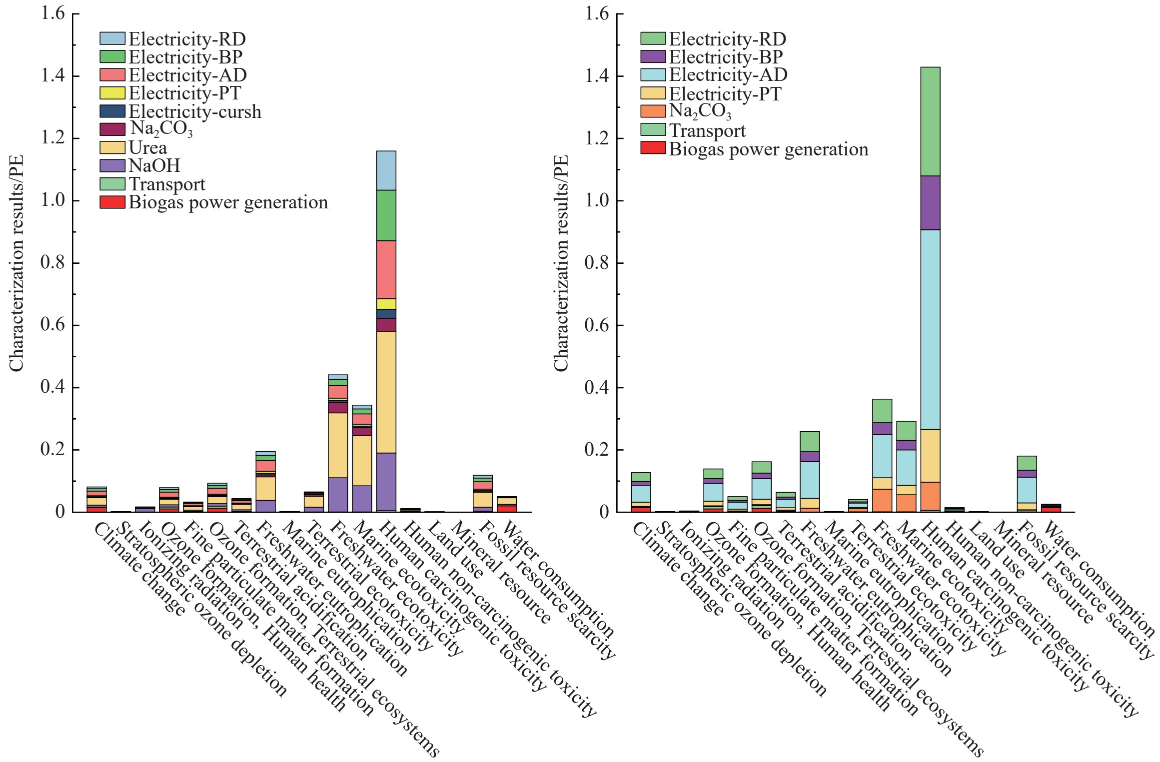


Figure 4 Comparative analysis of 18 mid-point impact categories of CSBP and DMBP

3.3 Environmental impact potential analysis

The characterization results of mid-point environmental impacts can only reflect the level of environmental impacts of the same type, and cannot compare different types of environmental impacts horizontally. This study standardized the data (standardized factors are listed in Table 3), converting different indicator results into environmental impact potential [unit: person equivalent (PE)], and making intuitive comparisons of various environmental impact types[57].

The standardization results are shown in Figure 5. The total standardized environmental impact potential of CSBP (2.739) is smaller than that of DMBP (3.159), indicating that DM as a fermentation raw material has a higher impact on the environment than CS. Compared to DM, the nutrient content in CS is lower, especially in terms of nitrogen and phosphorus content. Therefore, when using CS as a fermentation raw material, relatively fewer nutrients are released into the soil and water. In addition, CS itself has less odor and volatile organic compounds, so the volatile substances generated during the AD process are relatively less, and the impact on the surrounding environment and human health is relatively small. Among all environmental indicators, the categories of human carcinogenic toxicity, freshwater ecotoxicity, marine ecotoxicity, freshwater eutrophication, fossil resource scarcity and climate change have a greater impact on the environment. Among them, the potential environmental impact of human carcinogenic toxicity accounts for the largest proportion, reaching 54.24% and 60.02% respectively (Figure 5). This is consistent with the results of Alengebawy et al.[24], who found in the LCA of biogas, briquette fuel and syngas that high consumption of diesel and electricity in biogas engineering would lead to high Human carcinogenic toxicity.



a. CSBP b. DMBP

Figure 5 Standardized results of 18 mid-point environmental impact indicators of CSBP (a) and DMBP (b)

Calculating the weight of environmental impact potential according to the different units of biogas engineering can analyze the specific sources of environmental impact and find ways to reduce environmental hazards. The environmental impact potential of different units of biogas engineering is shown in Figure 6. The proportion of transport units in the entire system is not high, only accounting for a portion of the fossil resource scarcity and human carcinogenic toxicity impact categories, which are 4.94% (CSBP), 4.42% (DMBP), 13.04% (CSBP), and 12.48% (DMBP), respectively. The exhaust gases generated by diesel trucks during transportation include nitrogen oxides (NO_x), particulate matter (PM2.5), polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs), among which particulate matter and polycyclic aromatic hydrocarbons are considered to have potential carcinogenicity. In addition, diesel vehicle exhaust emissions also contain some metal elements, such as cadmium and nickel. These metal elements are also considered to have potential carcinogenic effects and are associated with diesel vehicle emissions[58]. The impact category of fossil resource scarcity in transport units is similar in the proportion of CSBP and DMBP, which is determined by the site selection of biogas engineering. The transportation distance significantly affects the energy and environmental performance of biogas plants[59], especially when using DM with low biogas yield. The transportation distances of the biogas engineering in this study are 30.59 km and 10 km, which are much lower than the requirement of a transportation distance of less than 64 km for large-scale biogas engineering[14].

Therefore, the proportion of transport units in the system in this study is relatively small. The pre-treatment units occupy a certain proportion of the entire system, which is mainly reflected in the pre-treatment agents used in CSBP[60]. Compared with DMBP, its proportion is 1.33 to 2.78 times higher in the above environmental impact categories, mainly reflected in the impact categories related to human health and environmental pollution. Due to the specific pre-treatment process of food in the cow's stomach, DM does not require specific chemical pre-treatment, which is the fundamental reason for the low environmental impact potential of its pre-treatment units[61,62].

Figure 6 shows that the AD units have the greatest environmental impact on the entire biogas project, with environmental impact potentials as high as 1.91 and 1.87 PE. Different studies have also shown that the AD operation stage of biogas engineering is the most severe stage of GHG emissions and environmental pollution throughout the entire life cycle[63]. The addition of the nutrient urea further enhances the proportion of AD units in CSBP, which is similar to Lan's research results[64]. Lan found that the nutrient production part in the AD stage has the most serious environmental impact over the whole life cycle. Therefore, the environmental impact of AD units primarily stems from the input of nutrients and the consumption of electricity. The selection of nutrients depends on the characteristics of the feedstocks, while the consumption of electricity depends on the degree of automation, stirring, pumping, and feeding frequency[65].

The waste disposal units related to electricity also occupy a certain proportion, and the proportion of DMBP in this unit is significantly higher than that of CSBP. For the FU of this study, the processing capacity of DM is obviously higher compared to CS, resulting in the environmental impact of its waste disposal units accounting for more than 20% of the total system. The main environmental impact of the biogas purification units results from Na_2CO_3. Due to the higher sulfur content of DM than CS (Table 2), more hydrogen sulfide is released during AD. The research of Wang et al. [66] shows that the selection of different desulfurization alkaline solutions has a significant impact on environmental characteristics, and its sensitivity is high. Therefore, it is crucial to screen more environmentally friendly and economically feasible desulfurization agents (such as a new type of iron oxide and active combination desulfurizer).

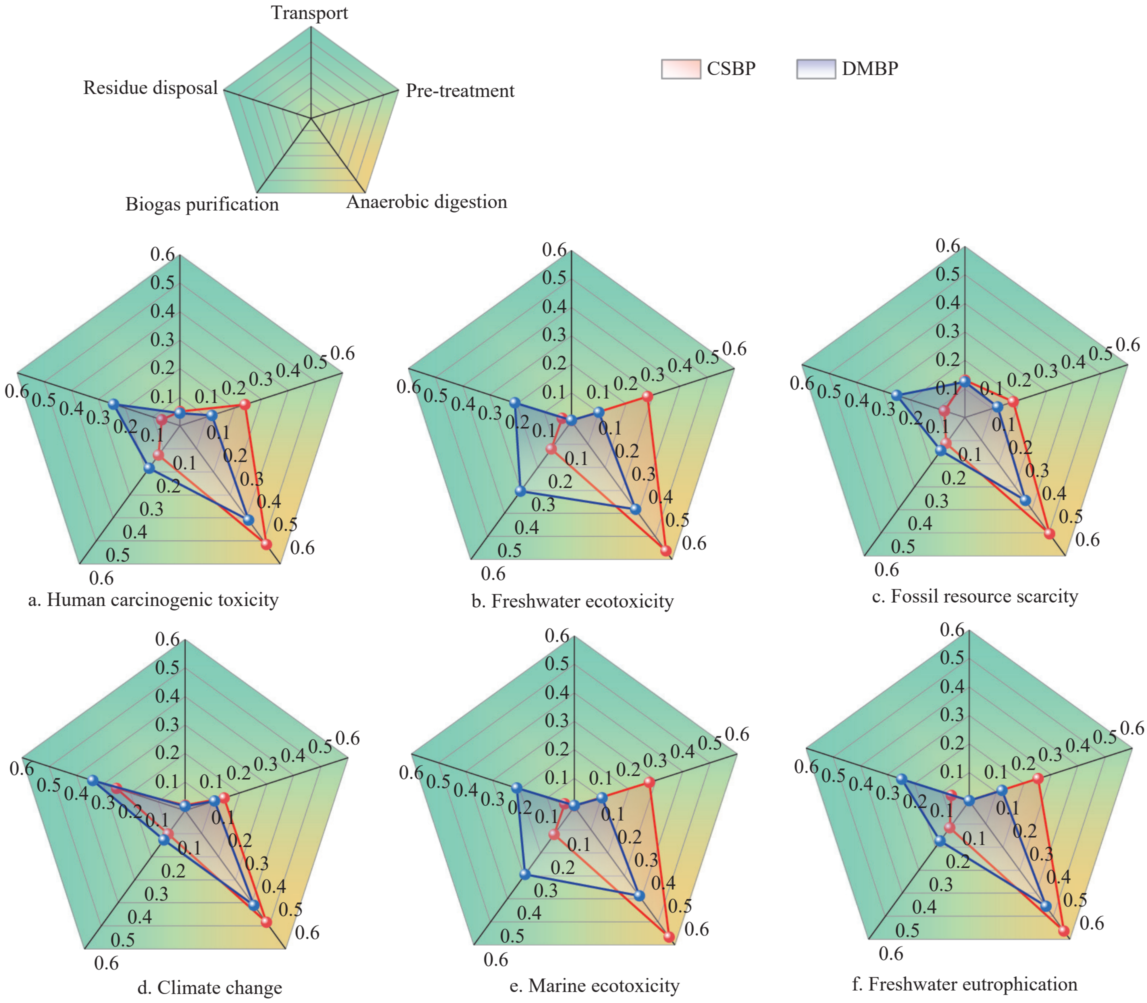


Figure 6 The proportion of environmental impact potential (a-f) of different units of CSBP and DMBP

3.4 End-point damage analysis of life cycle

The end-point method is a destruction-oriented method[51], which corresponds 18 impact categories to 3 damage types to obtain the weight results of the entire stage of biogas engineering under the damage types, as listed in Table 5. The ecological index factor is utilized to express this result, with Pt as the unit. To compare the impact of two biogas projects on the environment, this study did not include the improvement effects of by-products and products on the environment during the mid-point analysis of the life cycle. To explore the ultimate impact of biogas engineering with different raw materials on ecology, organic fertilizer is added to the residue disposal units, and biogas power generation is added to the Biogas purification units to form a new clean energy production unit. In Table 5, positive numbers indicate an adverse impact on the type of impact, while negative numbers have an improvement effect on the type of impact[67]. The ecological indices of human health for the two biogas projects are 37.834 and 26.234 Pt, respectively, which are not conducive to human health. This mainly comes from the pre-treatment process and AD process, and the huge demand for electricity comes from coalfired power plants, which emit gaseous pollution that is detrimental to human health. In addition, the use of chemicals in the pre-treatment process is the main reason why the human health ecological index factor of CSBP is higher than that of DMBP. The ecosystem quality and ecological index factor of resources for both are less than zero[68].

Among them, the resource improvement effect of CSBP is stronger, while the ecosystem quality improvement of DMBP is stronger, which is consistent with the conclusion obtained in Figure 3. The comprehensive ecological index factor of CSBP is –10.297 Pt, which is higher than the –6.192 Pt of DMBP, indicating that agricultural waste biogas production is a beneficial way for the environment, while CS is a more environmentally friendly raw material. The beneficial effects of biogas engineering mainly come from the resource utilization of engineering waste and the production of clean energy[69]. The low energy value of DM and the low efficiency of biogas conversion are the reasons why its environmental benefits cannot be maximized. However, DM has a good emission reduction benefits, which cannot be ignored[70]. In short, selecting suitable raw materials based on different environmental pollution restrictions and the actual situation of local waste resources is a concern that needs to be paid attention to.

Table 6 lists the results of the ecological index factor of this study and other studies on large-scale biogas plants. The raw material of the large-scale biogas project studied by Wang et al.[66] is stover, while Kan et al.[71] is manure. Their results of comprehensive ecological index were –9.510 Pt and 7.481 Pt, respectively, which is consistent with the results of the present study. The reasons for the different comprehensive ecological index values may be the differences in the actual operation conditions and processes of biogas projects. In the future, it can be committed to improving the process conditions of large-scale biogas projects, innovation of technical means and selection of raw materials, which will undoubtedly reduce the adverse impact of irrational disposal of agricultural waste on the environment.

Table 5 The weight analysis results of three damage categories (Pt)

Damage categories	CSBP					
	Transport	Pre-treatment	Anaerobic digestion	Clean power generation	Waste disposal	Total
Human health	5.301	24.660	37.710	–16.578	–13.259	37.834
Ecosystem quality	1.465	12.521	15.883	–23.823	–29.265	–23.219
Resources	2.365	6.652	9.489	–8.541	–34.876	–24.912
Total	9.131	43.833	63.081	–48.942	–77.4	–10.297
	DMBP					
Human health	6.701	12.660	41.710	–25.578	–9.259	26.234
Ecosystem quality	1.865	7.521	21.883	–33.823	–22.265	–24.819
Resources	2.665	10.652	17.489	–12.541	–25.872	–7.607
Total	11.231	30.833	81.082	–71.942	–57.396	–6.192

Table 6 Comparison of ecological index factor in different studies (Pt)

Human health	Ecosystem quality	Resources	Total	Reference
37.834	–23.219	–24.912	–10.297	CSBP (This study)
26.234	–24.819	–7.607	–6.192	DMBP (This study)
18.750	–5.440	–22.820	–9.510	Wang et al.[66] (2016)
5.624	0.200	1.657	7.481	Kan et al.[71] (2015)

4 Conclusions

In the two biogas projects, CSBP has a higher net energy efficiency (763.903 kW·h/FU) and DMBP has a higher GHG emission reduction (5541.418 CO_2-eq/FU). Both CSBP and DMBP are beneficial to the ecological environment, and their beneficial effects come from the utilization of biogas residue and the production of clean energy. Due to low biogas production, the economy of DMBP is poor, and the comprehensive ecological index factor is lower than that of CSBP (–10.297 Pt). However, CSBP still has the possibility to harm human health, so more sustainable methods should be sought to promote the development of biogas projects. Co-digestion can reduce the input of chemical substances and power consumption, and increase the yield of biogas, which is very beneficial to the environment.

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