Improving agricultural straw preparation logistics stream in bio-methane production: experimental studies and application analysis

Luo Tao¹ · Pan Juntong² · Meng Xi³ · Huang Hailong¹ · Long Yan¹ · Xiong Xia¹ · Huang Ruyi¹ · Mei Zili¹

Received: 23 May 2017 / Accepted: 3 August 2017 / Published online: 16 August 2017
© Springer-Verlag GmbH Germany 2017

Abstract Long-term production in commercial straw biogas plants has been rare in China due to inefficiencies in the logistics stream. Biomass densification could be a potential solution to this issue. Therefore, we conducted a study to evaluate whether biomass densification is a more efficient and sustainable option. We performed methane production experiments to investigate fermentation characteristics of briquettes (with a new pretreatment, model II) and rubs (with a common pretreatment, model I). A 3000-m³ biogas plant was used to conduct a comparative analysis with solar eMergy joules. Results showed that the methane yield of briquettes of corn stover was 66.74% higher than that of rubs, and the briquettes had better digestion performance in terms of CH₄ content, VFA, and alcohol. The two models required almost the same eMergy investment input, while model II obtained a greater quantity of net eMergy (16.5% higher) in comparison with model I. The net eMergy yield ratio (EYR) (biogas only) of model I and model II was 0.99 and 1.67, respectively, showing less market competitiveness for commercial operations with model I. Meanwhile,

the logistic costs of model II could be reduced to approximately US \$34,514 annually.

Keywords Feedstock · Biomass densification · Model · Biogas plant · Corn stove

Introduction

Anaerobic digestion is considered one of the most efficient ways to achieve comprehensive utilization of agricultural straw. However, preparation processes are typically not cost effective when straw is used as feedstock for biogas plants (Mussoline et al. 2013). Straw piles are very low in bulk density, which results in high costs in collection, transportation, storage, and pretreatment (Luo et al. 2015; Mussoline et al. 2013; Kadam et al. 2000). Reducing straw preparation costs (such as increasing the bulk density for easy storage) by optimizing the process for higher system efficiency has become a key goal for commercial straw biogas plants.

Currently, the logistics stream for feedstock of straw biogas plants (model I) mainly includes mechanical collection, storage, rubbing (or smashing), and feeding for biogas fermentation. There are two serious problems with model I. First, the seasonal collection of straw requires a large amount of area for long-term storage. Second, there is a great potential risk of fire. Biomass densification could be a possible solution to these problems.

Li et al. reported that densified straw can be completely auto-swollen into water within 24 h, when used as the feedstock, and the sugar conversion rate can be improved at the same time, compared with the raw state (Li et al. 2014). This could be a promising approach to improving biogas production. In this study, we proposed that it is possible to modify the feedstock preparation model to an

Luo Tao and Pan Juntong contributed equally to this work and should be considered co-first authors.

✉ Luo Tao
18782012718@163.com

¹ Biogas Institute of Ministry of Agriculture (BIOMA), Chengdu 610041, People's Republic of China

² Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, People's Republic of China

³ College Architecture and Urban Rural Planning, Sichuan Agriculture University, Chengdu 610065, People's Republic of China

optimal model (model II), consisting of collecting, rubbing (smashing), briquetting, storing, and feeding straw for biogas fermentation.

Biomass collection and transportation methods, as well as different straw mechanical pretreatment technologies, have been thoroughly analyzed by previous researchers (Kocoloski et al. 2011; Zhang and Ma 2015; Zhao et al. 2010). Nevertheless, these studies have rarely focused on the optimal straw storage process and the fermentation characteristics after condensing. To investigate the fermentation characteristics, paired observation was conducted on the biogas yield and fermentation performance of a corn stover that had been initially pretreated separately by rubbing and briquetting.

Based on the results, a 3000-m³ straw biogas plant was studied with the two different preparation logistics stream models using a sustainable and environmental accounting methodology based on the renewable perspective. We assumed that processes with higher level renewable resource recovery were likely to be more sustainable than those with a lower level (Martin et al. 2006).

The eMergy analysis methodology, developed by H. T. Odum, makes it possible to convert all of the inputs and outputs in a bio-methane production system into solar eMergy joules, which can help in analysis of problems in preparing feedstock with different amounts of energy. eMergy analysis is considered a practical method for assessing various downstream chains of products to identify the process with the larger percentage of renewable resources (Odum 1997; Brown and Ulgiati 2016). Sustainability cannot be truly evaluated at any scale without consideration of boundary conditions. Nevertheless, eMergy analysis has many more advantages in comparison to conventional methods, such as Life Cycle Assessment (LCA), which has not been able to handle the diversity of resources and their use (Zhang et al. 2017; Blengini et al. 2011). Abiotic depletion potential and surplus energy are only suited for non-renewable resources. Other methods, such as material flow analysis (MAF) and net energy analysis (NEA), have been developed to quantify reliance on the life cycle of natural resources. However, these methods could not capture and combine the quality differences between different resources.

Finally, we conducted an economic analysis to compare the economic performance of two straw preparation models. From a visual comparison, model II increases the financial input and the energy input of straw briquetting, and reduces the construction costs for the storage site and the costs of post-management and maintenance. Model I represents a comparatively complex process, as rubbing should be done before each feeding. In contrast, the feedstock only has to be prepared once overall in model II, thus reducing a lot of labor input.

With these results, it was possible to compare the costs and benefits for each of the two different options. From this, we could determine which of the preparation logistics streams (model I or model II) is better suited for the commercial operation of a straw biogas plant.

Materials and methods

Lab experimental design

To investigate the fermentation characteristics of briquetting biomass, anaerobic lab batch digestion tests were carried out in triplicate at 35 °C for 30 d in a water bath according to the method described by Wang et al. (2012). Each batch reactor had 1-L capacity and contained 500 mL of substrate. The initial volatile solid (VS) ratio of inoculums to substrate was kept at 2:1 for all of the experimental setups. The total solid content (TS) was 8% at setup.

The inoculum used in this study was obtained from a mesophilic anaerobic digester near Chengdu, China. The employed briquettes and rubs, and their corresponding raw materials in this work were collected from Heilongjiang province in northeast China, which mainly consisted of corn leaves and corn stalks, as shown in Fig. 1.

The raw materials were pressed with a ring die briquette machine (9SYH-1200, WanGuo Bioenergy Technology Co., Ltd., Xuzhou, Jiangsu Province, China) with a working pressure of approximately 2600 kg cm⁻² and a capability of approximately 1000–1600 kg h⁻¹. The resulting briquettes were cubes of approximately 30 × 30 mm in cross section, and 50–150 mm in length. The raw materials were rubbed to a size of 30–50 mm by an auger-type rubbing machine (9RS-600, Yike Industry Machinery Manufacturing Co., Ltd., Zhengzhou, Henan Province, China). The main characteristics of the substrates and the inoculum are shown in Table 1.

TS, VS, total carbon, and total nitrogen were determined according to the Standard Methods for the Examination of Water and Wastewater (APHA 2005). Biogas production was measured by the displacement of water. The volumes of biogas were normalized to the standard conditions (15°C, 101.325 K), and the methane (CH₄) contents in the biogas were analyzed with a gas analyzer (Gasboard-3200, Cubic, Wuhan, China).

Application analysis

Biogas plant system

The operating process of the plant could be divided into three different phases:

Fig. 1 The **a** rubs and **b** briquettes used in the corn stover for anaerobic digestion

Table 1 Inoculum and substrate characteristics

Material	Unit density (g/cm ³)	TS* (%)	VS* (%)	Total carbon (%)*	Total nitrogen (%)*	Carbon to nitrogen ratio (C/N)*
Rubs	0.06	89.82	77.57	40.3	0.76	53.03
Briquettes	1.49	91.08	67.51	ND	ND	ND
Inoculum	ND	10.69	48.60	2.31	0.81	2.85

ND not determined

* Based on the wet weight

1. Feedstock preparation: collection, transportation, storage, and pretreatment;
2. Anaerobic digestion;
3. Disposal of biogas and bio-fertilizer.

The managed biogas plant considered in this study is located in Henan, China. The mass flow rate of the feedstock rubbing biomass or briquetting biomass was about 120 t/d, and the effective volume of the digester was 3000 m³. TS content was fixed at about 8%, and mesophilic (35 °C) was employed, with the biogas yields calculated according to the lab experiment results. The assumed feedstock was the same and was collected nearby. The system was run in the two models, as shown in Fig. 2. Conventional rubbing devices cannot reduce the particle size of straw to meet the requirements of fine feedstock (less than 10 mm) for single-step manufacturing because of irregularities in powder size distribution (Lee and Mani 2017), which pose feedstock clogging problems for continuous biogas production. Thus, multiple rubbings are needed to feed the rice straw into normal anaerobic digesters without densification, which could crush the straw to satisfy further pretreatment demands (Luo et al. 2015).

The specific description of the feedstock preparation and parameters is presented in Table 2. The main parameters were obtained from the biogas plants in Anyang city, Henan province, China.

EMergy analysis

EMergy analysis is a systematic analysis method capable of taking into account all of the inputs and outputs of the socio-economic system, using the unit of solar eMergy joules (sej) (Sha et al. 2015). In this study, eMergy analysis results were used to evaluate alternative models of biomass feedstock preparation, referring to their eMergy investment and eMergy recovery (benefits) (as reported in an analysis of net eMergy yield of bioenergy stations in a Beijing suburb) by establishing long-term sustainability and measuring contributions to global environmental stress (Hu et al. 2009; Wang et al. 2016b). Figure 3 presents system eMergy diagrams of the biogas plant with different straw preparation models.

To convert all of the flows involved in the process into this common basis, conversion factors are used. The (solar) transformity is defined as the eMergy per unit flow or unit product. The different transformity on the energy content of each item was calculated by the energy from Hu et al. (2009) and Marchettini et al. (2007), and the formulas from Odum (1997). Various indicators were used for eMergy analysis. “eMergy investment” is useful in calculation of the environmental costs of treating the straw according to the given technologies. “eMergy recovery” measures how much eMergy has been saved using biogas and bio-fertilizer. The combination of these two indicators generates a net eMergy yield ratio (eMergy recovery/eMergy

Fig. 2 Straw preparation logistics streams, model I and model II

Table 2 Description of feedstock preparation and process parameters

Items	Description
Collection (Wang et al. 2011)	Collection of biomass after crop harvest, mainly including: baling, unloading/hauling to roadside, preparation
Transportation*	Truck transport from the roadside to biogas plant
Storage	Storage site should have a hard surface to ensure access during wet periods of the year. Also, high winds, arson, rodents, and fugitive dust also are factors to consider. It is designed in accordance with the local standard (2142-2012 2012)
Pretreatment	
(a) Model I	
Rubbing	Equipment depreciation charge, equipment maintenance, fuel costs, labor costs. This study used a 9RS-600 agitating and rubbing machine: 15 KW, 2–4 t/h, Zhengzhou Yike Heavy Machinery Manufacturing Company, service life 5 years
(b) Model II	
Rubbing and briquetting	Equipment depreciation charge, equipment maintenance, fuel costs, labor costs. This study used a 9RS-600 agitating and rubbing machine and 9JY-3000A type straw briquetting machine: 90 KW, 2000–3000 kg/h, Hebei Tiantai Biomass Development Co., Ltd., service life 5 years

* The energy input of transportation was calculated as $0.06 \text{ L}/(\text{t km}) \times 38.4434 \text{ MJ/L} = 2.306 \text{ MJ}/(\text{t km})$ (Xing et al. 2008). Since the arable land rate is 37.68% in China, the collection radius of the project was 2.35 km. In addition, because transportation does not follow a straight line, a flection factor was used. In view of the small quantity of straw collected, the collection radius was the transportation radius (Overend 1982; Kocoloski et al. 2011)

Fig. 3 eMergy diagrams of the biogas plant with different biomass preparation models

investment, EYR) and net eMergy (eMergy recovery minus eMergy investment).

Results and discussion

Methane production characteristics

Figure 4 shows the daily biogas production and cumulative biogas production during the 30-day tests. Three obvious

peaks of daily methane production were observed during the digestion process, and this was similar to other research findings in relation to corn stovers (Pang et al. 2008). Three days later, the first daily biogas production peaks appeared for both. At this point, the daily methane production reached 85.73 and 68.16 for briquettes and rubs, respectively. Daily methane production of rubs then tended to decrease during the following 5–6 days, and then resumed increasing, finally reaching the highest level of production. However, the methane production of briquettes increased

more consistently, quickly reaching a high biogas production rate with only one day of decrease.

On days 6–14, the methane production rate of briquettes remained at a high level of more than 300 mL/d. Nevertheless, the similar period for rubs was only during days 9–11, and was 33.3% that of the briquettes. The highest daily methane production was observed on day 10, and the highest methane production rate was 489.75 mL/d for briquettes, which was higher than that of rubs by 19.61%.

Based on the cumulative biogas production at different stirring rates shown in Fig. 4b, briquetting was an important parameter for improving methane production with significantly higher cumulative biogas production than rubbing. Meanwhile, the methane yield of briquetting was 181.33 mL/g, 66.74% higher than that of rubbing. This was possibly caused by an increase in the degradation of straw, including cellulose, hemicellulose and lignin (Wang et al. 2016a). Briquetting is a high pressure and high temperature process, and when the temperature is greater than 100 °C, it promotes dissolution of lignin and improves biogas production (Amnuaycheewa et al. 2016).

Anaerobic digestion process

Figure 5a shows the methane content profile during the 30-day digestion. The methane content can be used to indicate whether the methanogens dominate the anaerobic digestion, and methane content in biogas is normally higher than 50% (Li et al. 2008). For the two pretreatments, the methane contents both started to increase and reached normal levels at day 5. Subsequently, the methane content of the briquettes remained in the normal range, 50–60%. The trend of methane content was similar to the normal

corn stover digestion described in previous studies (Shen et al. 2013).

Volatile fatty acids (VFAs) and alcohol production are considered the most important parameters of anaerobic digestion during the acidogenesis and acetogenesis steps because they control methanogenic populations, anaerobic digestion efficiency, and the buffering capacity of the substrate that ultimately accounts for methane generation (Zhu et al. 2010). As Fig. 3b shows, during the entire experiment, the VFA concentrations were relatively low compared to the reported normal digestion level of 2880 mg/L (Lindorfer et al. 2008). We assumed that inhibition was not reached, and the low VFA concentration was beneficial to steady methane production. Furthermore, maximum VFA for rubs was 920.85 mg/L, recorded on day 5, and for briquettes was 950.93 mg/L, recorded on day 10, at which point the daily methane production for rubs was nearly at the lowest level, as Fig. 2a shows. These results support the finding that VFA accumulation caused the least amount of methane production during the acidogenesis step since methanogens were restrained (Gomez-Tovar et al. 2012). For briquettes, daily methane production was at its highest level since methanogens occupied the main position, and VFAs could be degraded and rapidly converted into methane. These results also supported the role of VFAs in the highest methane production.

A similar trend for alcohol production is shown in Fig. 5b. Almost 100% alcohol stabilization was observed since it was readily consumed during the anaerobic digestion process. The highest levels of alcohol productions at 159.3 and 199.7 mg/L were recorded for rubs and briquettes, respectively. Alcohol production was also

Fig. 4 Biogas production in the lab experiment

Fig. 5 Methane content, VFA, and alcohol concentration of the lab experiment

beneficial for methane production, as shown in a previous study of an untreated corn stover (Hassan et al. 2016).

The above data and analysis proved that biomass briquetting could improve the stability of anaerobic digestion.

EMergy analysis

Investment and recovery

In Tables 3 and 4, the results of the analysis performed on the two models for a 3000-m³ biogas plant are presented with two similar anaerobic phases and one different one. The feedstock phases could be divided into three parts: straw collection, transportation, pretreatment (model I: rubbing; model II: rubbing and briquetting), and storage.

Analysis of the biogas plant shows that the feedstock preparation processes take the most important role in eMergy investment with almost no difference between the two models, requiring 52.4 and 52.5% of the total eMergy cost with model I and model II, respectively. For more detailed analysis, the straw collection, transportation, storage and pretreatment for rubs cost 50.4, 6.3, and 43.3% of the feedstock preparation investment, respectively, while for briquettes these elements cost 50.2, 6.3, and 43.5%, respectively. The most significant inputs of model I include rubbing labor and straw storage site costs, while that of model II includes the electricity used in making the briquettes. However, the eMergy requirements are almost equal for two main reasons. On the one hand, the densification process can obviously improve the efficiency of pretreatment in centralized processing and reduce eMergy input, while the pretreatment must be carried out before each feeding time with model I. On the other hand, the investment in the storage phase drops dramatically in terms of straw yard costs due to construction area demands and

fire management requirements. Specifically, investment in fire control facilities will increase several times with increases in straw yard area because of higher critical fire ratings, as is required by Chinese national standards, “Code of Design on Building Fire Protection and Prevention” (GB50016-2014 2015).

As depicted above, a large part of the cost and area for straw storage can be saved with model II. In addition, the safety of storage and the methane yield of straw can also be improved. Transportation costs were low since trucks are the most feasible option in the feedstock preparation systems, and the transportation distance was not great when feedstock was nearby. It is clear that the costs of densification will drop sharply for long distance transportation, with large increases in the amount of biomass carried by each truck. The energy inputs of briquetting are still relatively high. Therefore, further work should focus on optimization of the pretreatment process, especially reducing the inputs of briquetting to obtain a more efficient logistic stream.

As Table 5 shows, eMergy recovery includes biogas and bio-fertilizer. The eMergy output from the biogas of model II is 67.5% higher than model I, about 4.19×10^{17} sej/year. Therefore, the eMergy input for briquetting is much more significantly efficient; furthermore, the output of biogas with model II meets the investment requirements, while it does not meet the investment requirements with model I. This study assumed that the rest of fermentation could be used completely, as the leachate could be recycled back to the digester. In that case, the major digestate of straw biogas plant is bio-sludge, and when it is used as bio-fertilizer, the nutrient contents are: $N = 4.13\%$, $P = 2.1\%$, $K = 0.9\%$, and organic matter = 11.5% (Ge et al. 2014). In fact, the quality of the final bio-fertilizer depends on the quality of the bio-slurry. The results from eMergy recovery

Table 3 Emergy investment of a 3000 m³ biogas plant with rubbing

Item	Unit	Amount (units/year)	Solar transformity (sej/year)	Solar eMergy (sej/year)
Straw collected	g	3.90E+09		
Feedstock preparing (1–10)				3.26E+17
(a) Straw collection				1.64E+17
1 Fuel	J	3.16E+10	6.60E+04	2.09E+15
2 Labor	J	1.10E+10	7.38E+06	8.12E+16
3 Machinery	\$	4.14E+04	1.96E+12	8.11E+16
(b) Transportation				2.05E+16
4 Fuel	J	2.11E+10	6.60E+04	1.39E+15
5 Labor	J	1.83E+09	7.38E+06	1.35E+16
6 Machinery	\$	2859.24	1.96E+12	5.60E+15
(c) Storage and rubbing				1.41E+17
7 Labor	J	4.38E+09	7.38E+06	3.23E+16
8 Electricity	J	1.05E+11	1.48E+05	1.55E+16
9 Machinery	\$	1759.54	1.96E+12	3.44E+15
10 Straw storage site cost	\$	4.68E+04	1.96E+12	9.17E+16
Anaerobic process (11–15)				2.96E+17
11 Fuel	J	7.89E+09	6.60E+04	5.21E+14
12 Labor	J	4.38E+09	7.38E+06	3.23E+16
13 Electricity	J	3.59E+11	1.48E+05	5.31E+16
14 Plant cost	\$	1.06E+05	1.96E+12	2.08E+17
15 Water	g	1.31E+10	2.03E+05	2.66E+15
Total eMergy investment (1–15)				6.23E+17

(Table 5) clearly show that the organic part of the total bio-slurry produced assumes the eMergy value of an equivalent amount of fertilizer, which is assumed to have the same content of P, K, and N.

Evaluation of the total eMergy

The results were reinforced by analysis of the EYR of the two models (Table 6). The indicators measure the benefit obtained with respect to the cost necessary to convert biomass. The EYRs show that the costs of the two models are lower than their benefits, so these models are both feasible. Nevertheless, eMergy output of the biogas plant with model II is higher than model I with the same amount of biomass inputs. It is also interesting to see that model II was able to save a greater quantity of net eMergy compared to model I, 16.5% higher. Therefore, model II is much more efficient in eMergy output.

The results depend on completely applying bio-slurry to farmland and using biogas and bio-fertilizer efficiently. However, in some cases, the consideration factor of output only includes biogas, as the bio-slurry cannot be accurately measured, so the EYR (biogas only) of model I was 0.99, less than 1. It was obvious that model I was less suited for

the biogas plant, lacking market competitiveness with commercial operations (Huang et al. 2013).

Economic analysis

As stated above, it is more sustainable to apply biomass densification for biogas production. To clarify economic feasibility, a preliminary estimation of the logistic costs of the two models was investigated according to the different feedstock preparation flows. The local labor input is 29.3 \$/day (8 h), and electricity price is about 0.123 \$/(kW h). The cost estimation was evaluated based on this information, and the results are presented in Table 7.

As indicated in Table 7, the electricity input harvest cost will increase by 247.2% due to densification as briquetting is employed. However, the feedstock preparation cost will be reduced. Storage costs will be reduced by 92.5% due to sharp decreases in construction and fire-fighting equipment inputs. Meanwhile, labor costs can be reduced by 40.7% because of the increased efficiencies in the process. Overall the total logistic costs with model II could be reduced to approximately US \$34,514 per year. As a result, we concluded that model II represents a feasible approach to apply biomass densification for logistic stream optimization.

Table 4 eMergy investment of a 3000 m³ biogas plant with rubbing and briquetting

Item	Unit	Amount (units/year)	Solar transformity (sej/year)	Solar eMergy (sej/year)
Straw collected	g	3.90E+09		
Feedstock preparing (1–10)				3.27E+17
(a) Straw collection				1.64E+17
1 Fuel	J	3.16E+10	6.60E+04	2.09E+15
2 Labor	J	1.10E+10	7.38E+06	8.12E+16
3 Machinery	\$	4.14E+04	1.96E+12	8.11E+16
(b) Transportation				2.05E+16
4 Fuel	J	2.11E+10	6.60E+04	1.39E+15
5 Labor	J	1.83E+09	7.38E+06	1.35E+16
6 Machinery	\$	2859.24	1.96E+12	5.60E+15
(c) Rubbing and briquetting and storage				1.42E+17
7 Labor	J	2.93E+09	7.38E+06	2.16E+16
8 Electricity	J	7.37E+11	1.48E+05	1.09E+17
9 Machinery	\$	2346.04	1.96E+12	4.60E+15
10 Straw storage site cost	\$	3.50E + 03	1.96E+12	6.86E+15
Anaerobic process (11–15)				2.96E+17
11 Fuel	J	7.89E+09	6.60E+04	5.21E+14
12 Labor	J	4.38E+09	7.38E+06	3.23E+16
13 Electricity	J	3.59E+11	1.48E+05	5.31E++16
14 Plant cost	\$	1.06E+05	1.96E+12	2.08E+17
15 Water	g	1.31E+10	2.03E+05	2.66E+15
Total investment (1–15)				6.23E+17

Table 5 eMergy recovery from the two models

Item	Unit	Amount (Units/year)	Solar transformity (sej/year)	Solar eMergy (sej/year)
eMergy recovery from biogas				
(a) Model I (rubbing)	J	1.37E+13	4.54E+04	6.21E+17
(b) Model II (rubbing and briquetting)	J	2.28E+13	4.54E+04	1.04E+18
eMergy recovery from bio-fertilizer				2.54E+18
1 N	g	1.81E+8	4.62E+9	8.36E+17
2 P	g	9.20E+7	1.78E+10	1.64E+18
3 K	g	3.94E+7	1.74E+9	6.79E+16
4 Organic matters	g	5.04E+8	1.24E+5	6.25E+13
Total eMergy recovery with rubbing				3.16E+18
Total eMergy recovery with rubbing and briquetting				3.58E+18

Conclusion

The experimental results indicated that biomass briquetting presented positive responses in methane production and stability of the anaerobic digestion process. eMergy was used to evaluate and compare model I (only rubbing) and model II (rubbing and briquetting) of the feedstock preparation processes. eMergy-based indicators were calculated and demonstrated a higher performance and

sustainability of model II compared to model I, including EYR and net eMergy. Furthermore, we determined that biogas plants operating with model II could reduce financial investment requirements and have better performances in biomass storage and operation.

Overall, model II is an outstanding feedstock preparation process for biogas plants. Its application is highly recommended for the feedstock preparation of straw biogas plants. Further work should be done to improve the

Table 6 EYR and net eMergy of the two models

Logistic streams	EYR (biogas only) ^a	EYR (biogas and bio-fertilizer) ^b	Net eMergy (sej/year)
Model I (rubbing)	0.99	5.07	2.54E+18
Model II (rubbing and briquetting)	1.67	5.74	2.96E+18

^a eMergy output is calculated including only biogas^b eMergy output is calculated including biogas and bio-fertilizer**Table 7** Cost estimation for the different logistic streams in model I and model II

Model I		Model II	
Input	Cost (\$/year)	Input	Cost (\$/year)
Straw bales storage	46,800	Rough rubbing and briquetting machinery	2346
Rough and further rubbing machinery	1760	Densified straw storage	3500
Labor input	24,100	Labor input	14,300
Electricity input	7200	Electricity input	25,200
Total	79,860	Total	45,346
Comparison	–	–	↓43.2%

technical level of the briquetting to reduce the eMergy investment.

Acknowledgements The authors gratefully acknowledge the financial support from the National Key Technology Support Program (2015BAD21B03) and the Sichuan Province Science and Technology Support Project (15ZC1450) and the Agricultural Science and Technology Innovation Program (ASTIP) of the Chinese Academy of Agricultural Sciences.

References

- 2142-2012 NT (2012) Process design code of crop straw anaerobic digestion engineering. China agriculture press, Beijing
- Amnuaycheewa P, Hengaroonprasan R, Rattanaporn K, Kirdponpatara S, Cheenkachorn K, Sriariyanun M (2016) Enhancing enzymatic hydrolysis and biogas production from rice straw by pretreatment with organic acids. *Ind Crops Prod* 87:247–254
- APHA (2005) Standard methods for the examination of water and wastewater (American Water Works Association and Water Environment Federation, 21st edn. American Public Health Association, Washington, D.C.
- Blengini GA, Brizio E, Cibrario M, Genon G (2011) LCA of bioenergy chains in Piedmont (Italy): a case study to support public decision makers towards sustainability. *Resour Conserv Recycl* 57:36–47
- Brown MT, Ulgiati S (2016) Emergy assessment of global renewable sources. *Ecol Model* 339:148–156
- GB50016-2014 (2015) Code of design on building fire protection and prevention. China Planning Press, Beijing
- Ge Z, Wei Y, Liu J, Zhao Y (2014) Characteristics of digestate and utilization: an overview *China Biogas* 32(3):74–82
- Gomez-Tovar F, Celis LB, Razo-Flores E, Alatrisme-Mondragón F (2012) Chemical and enzymatic sequential pretreatment of oat straw for methane production. *Biores Technol* 116:372–378
- Hassan M, Ding W, Bi J, Mehryar E, Talha ZAA, Huang H (2016) Methane enhancement through oxidative cleavage and alkali solubilization pre-treatments for corn stover with anaerobic activated sludge. *Biores Technol* 200:405–412
- Hu Y, Zhou L, Li H, Wang A, Shi D, Wang Y, Yan M (2009) Evaluation and analysis of net emergy yield of two bio-energy stations in Beijing suburb. *Trans Chin Soc Agric Eng* 25(8):200–203
- Huang C, Deng L, Gao X, Luo Y, Zhang S, Liu L (2013) Rural housing land consolidation and transformation of rural villages under the “coordinating urban and rural construction land” policy: a case of Chengdu city, China. *Low Carbon Econ* 4:95–103
- Kadam KL, Forrest LH, Jacobson WA (2000) Rice straw as a lignocellulosic resource: collection, processing, transportation, and environmental aspects. *Biomass Bioenerg* 18(5):369–389
- Kocoloski M, Griffin WM, Matthews HS (2011) Impacts of facility size and location decisions on ethanol production cost. *Energy Policy* 39(1):47–56
- Lee H, Mani S (2017) Mechanical pretreatment of cellulose pulp to produce cellulose nanofibrils using a dry grinding method. *Ind Crops Prod* 104:179–187
- Li RP, Liu YP, Li XJ (2008) Biogasification performance of anaerobic co-digestion of kitchen residues and cattle manure. *Kezaisheng Nengyuan/Renew Energy Resour* 26(2):64–68
- Li Y, Li X, Shen F, Wang Z, Yang G, Lin L, Zhang Y, Zeng Y, Deng S (2014) Responses of biomass briquetting and pelleting to water-involved pretreatments and subsequent enzymatic hydrolysis. *Biores Technol* 151:54–62
- Lindorfer H, Waltenberger R, Koellner K, Braun R, Kirchmayr R (2008) New data on temperature optimum and temperature changes in energy crop digesters. *Biores Technol* 99(15):7011–7019
- Luo T, Long Y, Li J, Meng X, Mei Z, Long E, Dai B (2015) Performance of a novel downward plug-flow anaerobic digester for methane production from chopped straw. *BioResources* 10(1):943–955

- Marchettini N, Ridolfi R, Rustici M (2007) An environmental analysis for comparing waste management options and strategies. *Waste Manag* 27(4):562–571
- Martin JF, Saw D, Powell E, Stanton M, Levytacher S (2006) Emergy evaluation of the performance and sustainability of three agricultural systems with different scales and management. *Agr Ecosyst Environ* 115(1):128–140
- Mussoline W, Esposito G, Giordano A, Lens P (2013) The anaerobic digestion of rice straw: a review. *Crit Rev Environ Sci Technol* 43(9):895–915
- Odum HT (1997) Environmental accounting: EMERGY and environmental decision making. *For Sci* 43(2):305
- Overend PR (1982) The average haul distance and transportation work factors for biomass delivered to a central plant. *Biomass Bioenerg* 2(3):75–79
- Pang Y, Liu Y, Li X, Wang K, Yuan H (2008) Improving biodegradability and biogas production of corn stover through sodium hydroxide solid state pretreatment. *Energy Fuels* 22(4):2761–2766
- Sha Z, Guan F, Wang J, Zhang Y, Liu H, Wang C (2015) Evaluation of raising geese in cornfields based on emergy analysis: a case study in southeastern Tibet, China. *Ecol Eng* 84:485–491
- Shen F, Tian L, Yuan H, Pang Y, Chen S, Zou D, Zhu B, Liu Y, Li X (2013) Improving the mixing performances of rice straw anaerobic digestion for higher biogas production by computational fluid dynamics (CFD) simulation. *Appl Biochem Biotechnol* 171(3):626–642
- Wang X, Xu B, Zhang C (2011) Cost-benefit analysis of the straw baling process Jiangsu agricultural mechanization 2(2):22–23
- Wang X, Yang G, Feng Y, Ren G (2012) Potential for biogas production from anaerobic co-digestion of dairy and chicken manure with corn stalks. In: Pan W, Ren JX, Li YG (eds) *Renewable and sustainable energy*, Pts 1–7, vol 347–353. *Advanced Materials Research*. pp 2484–2492. doi:10.4028/www.scientific.net/AMR.347-353.2484
- Wang D, Huang H, Shen F, Yang G, Zhang Y, Deng SH, Zhang J, Zeng Y, Hu Y (2016a) Effects of biomass densification on anaerobic digestion for biogas production. *RSC Adv* 6:91748–91755
- Wang X, Wu X, Yan P, Gao W, Chen Y, Sui P (2016b) Integrated analysis on economic and environmental consequences of livestock husbandry on different scale in China. *J Clean Prod* 119:1–12
- Xing A, Liu G, Wang Y, Wei F, Jin Y (2008) Economic, energy and environment analysis on biomass collection process. *Chin J Process Eng* 8(2):305–313
- Zhang X, Ma F (2015) Emergy evaluation of different straw reuse technologies in Northeast China. *Sustainability* 7(9):11360–11377
- Zhang LX, Hao Y, Chang Y, Pang MY, Tang SJ (2017) Emergy based resource intensities of industry sectors in China. *J Clean Prod* 142:829–836
- Zhao R, Zhang Z, Zhang R, Li M, Lei Z, Utsumi M, Sugiura N (2010) Methane production from rice straw pretreated by a mixture of acetic-propionic acid. *Biores Technol* 101(3):990–994
- Zhu J, Wan C, Li Y (2010) Enhanced solid-state anaerobic digestion of corn stover by alkaline pretreatment. *Biores Technol* 101(19):7523–7528