academicJournals

Vol. 14(22), pp. 1910-1917, 3 June, 2015
DOI: 10.5897/AJB2015.14603
Article Number: 32458CC53410
ISSN 1684-5315

http://www.academicjournals.org/AJB

African Journal of Biotechnology

Full Length Research Paper

Evaluation of methane production features and kinetics of *Bougainvillea spectabilis* Willd waste under mesophilic conditions

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Received 16 March, 2015; Accepted 15 May, 2015

The objective of this study was to investigate and evaluate the biomethane potential (BMP) of *Bougainvillea spectabilis* Willd waste in Yunnan, China, when subjected to mesophilic anaerobic digestion (AD). Three different categories of plant waste investigated were as follows: the flowers, leaves and stems of *B. spectabilia*. These three portions were assessed for their BMP in a laboratory-scale batch anaerobic digester for a period of 60 days at 30±0.1°C temperature. The results show that maximum daily methane yield of *B. spectabilia's* flowers, leaves and stems were 65.95, 56.29 and 18.8 mL/(g.VS), respectively. Moreover, the research used substrate kinetics, including the Gompertz equation, the logistic equation and the transference function to analyze the AD process. All models fit the experimental data with R^2>0.993. However, the Gompertz equation presented the best agreement in the fitting progress.

Key words: *Bougainvillea spectabilis* Willd, biomethane potential, anaerobic digestion, mathematical model.

INTRODUCTION

Bougainvillea spectabilis Willd (BSW) is a flowering, ornamental plant and is economically important to tropical and subtropical regions (Mohammad et al., 2013). In China's subtropical Yunnan Province, the *Bougainvillea* plant can be seen everywhere. In fact, it is one of the main urban plants, particularly in Yunnan's capital, Kunming. In the course of natural growth and pruning, BSW produces a great deal of leaves, branches and other plant material that accumulates and must be removed. The Chinese Government presently regards the greenery as waste and has taken some measures to treat it. At present, large cities, for instance Beijing, Shanghai and Guangzhou, have started to manage this waste with formal classification as green waste, grinding and composting. After being mulched, this waste can become organic fertilizer for soil improvement and landscaping.

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Abbreviations: AD, Anaerobic digestion; **BMP,** biomethane potential; **BSW,** *Bougainvillea spectabilis* Willd; **GHG,** greenhouse Gas; **TS,** total solids; **VS,** volatile solids.

However, in Kunming, green waste is chiefly landfilled and does not receive any effective treatment.

Green waste management systems in developing countries like China must address many challenges, including limited technical experience and financial resources that frequently cover only collection and transfer costs and leave no resources for safe and sustainable treatment (Tadesse et al., 2014). If we take measures to deal with the great deal of green waste by burning it, it will generate significant greenhouse gas (GHG) emissions. Meanwhile, the escalating prices of conventional energy sources and global warming issues have compelled to promote sustainable renewable energy. Among the many options available for treatment of municipal green waste, the anaerobic digestion treatment process is sustainable and cost-effective because of its capacity to capture not only nutrients but also energy production (biogas) and anaerobic digestate as agricultural fertilizer. In recent years, the conversion of municipal green waste to biogas has become increasingly popular in industrialized nations as a means of turning a liability into an asset. Various relatively advanced designs have evolved at different scales, but significant potential for increased biogas use still exists.

Biogas production depends on a number of factors. Chief among them are the volatile solids (VS) content of the feedstock and the parameters of the biological community that inhabits the digester (Macias et al., 2008). Additionally, according to Kayhanian (1995) and Hartmann et al. (2004), the type of plant waste – particularly the amount of lingocellulose material (composition of lignin, cellulose and hemicellulose) it contains – influences biological activity and hence the biodegradability of the waste. Biogas production rates and the activity of anaerobic microorganisms are also influenced by the balance of carbon and nitrogen in the feedstock. The C/N ratio should range between 25:1 and 30:1 for proper anaerobic digestion (Fricke et al., 2007).

Environmental factors such as high or low temperature and pH also determine the efficiency of biogas production (Mashad, 2004). This suggests that the BMP of green waste has to be determined according to local environmental conditions and any unique characteristics of local waste. However, from the literature survey, the scientific study on this topic currently scarce in, particularly with regard to the BMP of the BSW that pervades Kunming. Considering this fact, this study, therefore, aimed to determine the biogas and biomethane production potential of the different components of BSW waste in Yunnan and comparable subtropical regions using a proximate analysis method. We used different model for instance, the Gompertz equation, the logistic equation and transference function to analyze the AD process stability and explore the biodegradability parameters of BSW.

Several researchers have used mathematical models in their studies to obtain kinetic parameters of the anaerobic digestion of energy crops. The first-order kinetic model used by Massė et al. (2010) and Mähnert et al. (2009) evaluated the BMP of switchgrass, maize silage and so on. The model fit the experiment data, and the coefficients of determination were higher than 0.99.

Based on existing knowledge, the main parameter considered in the previous studies is the final amount of biogas produced (total cumulative biogas yield); only a few studies investigated the biogas production rate. In the current paper, anaerobic digestion tests were conducted to determine the biogas production of BSW, mainly focusing on the biogas production. Additionally, the three above mentioned mathematical models were used to evaluate biogas production rate using obtained experimental data.

MATERIALS AND METHODS

Feedstock and inoculum

Flowers, leaves and stems of fresh BSW were collected from Yunnan Normal University's Chenggong campus. Flowers and leaves were cut into small fragments and the stems into 0.5 cm pieces. This feedstock did not receive any chemical pretreatment. Total solids content (TS) of BSW flowers, leaves and stems were 24.02, 28.71 and 24.83%, respectively. The volatile solid content (VS) of flowers leaves and stems were 20.77, 23.39 and 21.20%, respectively.

Inoculum was taken from a mesophilic anaerobic digestion reactor fed with swine manure (30°C well-run anaerobic digester). Before use, inoculum was sieved through a sieve of 1 mm mesh to remove large particles and grit. The pH, TS content, and VS content, of the sieved inoculum were 7.3, 32.31 and 27.62%, respectively.

Experimental set up and procedure

Anaerobic digestion experiments were carried out in 500 ml glass bottles at 30±0.1°C with a working volume of 400 ml. Firstly, inoculum (120 g) was added to each bottle, followed by the addition of substrate with a substrate to inoculum (S/I) ratio of 0.75 (flowers), 0.85 (leaves), 0.77 (stems) based on VS content. Then, all bottles were filled with 400 ml water. Finally, 3 mol/L sodium hydroxide (NaOH) was added as a buffering agent. The headspaces of the digesters were flushed with N_2-gas for 2 min to remove the residual oxygen and ensure anaerobic condition. After then, the bottles were sealed with butyl rubber stoppers. Biogas potential tests were performed under mesophilic conditions (30±0.1°C) controlled by a water bath. Bottles were mixed automatically once per hour. The experiment period was about 60 days. Biogas production was measured in mL and later adjusted to normal (standard) conditions: 273 K and 1,013 mbar. Bottles with inoculum only were used to determine the methane produced from it. The methane produced from inoculum only was subtracted from the bottles containing substrate and inoculums when calculating the biogas yield from the substrates alone. The instrumental set-up consists of a sample incubation unit (A), a CO_2-fixing unit (B) and a gas volume meter (C) (Figure 1).

A pH indicator (that is, thymolphthalein) was added to each bottle to control the acid-binding capacity of the solution. The volume of CH_4 released from the CO_2-fixing unit was measured using a wet gas flow measuring device with a multi-flow cell arrangement (15 cells). This measuring device can monitor low gas flows and works

Figure 1. Photograph of AMPTS II.

Table 1. Model and Equations.

Model	Equation
Modified Gompertz equation	$M = P \times \exp\left\{-\exp\left[\frac{R_m \times e}{P}(\lambda - t) + 1\right]\right\}$
Transference function	$M = P \times \left\{1 - \exp\left[-\frac{R_m(t-\lambda)}{P}\right]\right\}$
Logistic function	$M = \frac{P}{1 + \exp\left[4R_m(\lambda - t)/P + 2\right]}$

according to the principle of liquid displacement and buoyancy; a digital pulse is generated when a defined volume of gas (that is, 5 mL) flows through the device. An integrated embedded data acquisition system is used to record, display and analyze the results.

Models for data fit

Three models were used to estimate performance parameters. The logistic function corresponds to established trends of biogas production kinetics: an initial exponential increase and a final stabilization at a maximum production level. Moreover, the logistic function is based mainly on four assumptions and is designed to be as simple as possible in order to avoid unidentifiable parameters (Bhatta et al., 2015). Similarly, the modified Gompertz equation can be used to analyze methane production; however, the three parameters of this model are restricted to specific experimental conditions and cannot be used in a predictive mode (Ye et al., 2015). The transference function predicts maximum gas production solely based on CH_4 production (Pommier et al., 2007).

In this study, after obtaining cumulative methane production curves over time from the AD tests, the modified Gompertz equation, logistic function and transference function (Table 1) as presented by Donoso-Bravo et al. (2010) were used to determine methane production potential (P), maximum rate of methane production (R_m) and duration of the lag phase (λ).

RESULTS AND DISCUSSION

Methane production

Cumulative methane production and daily methane production as a function of time for BSW flowers, leaves and stems are presented in Figures 2 and 3, respectively. From the Figure 2, the specific methane yield of BSW flowers increased from 0.6 to 1369 mL. Similarly, the specific methane yield of BSW leaves increased from 0.3 to 1351 mL, achieving the same production trend as like flowers. The final outputs are almost identical in flowers and leaves. However, the specific methane yield of BSW stems merely increased from 0.3 to 960 mL. Specific

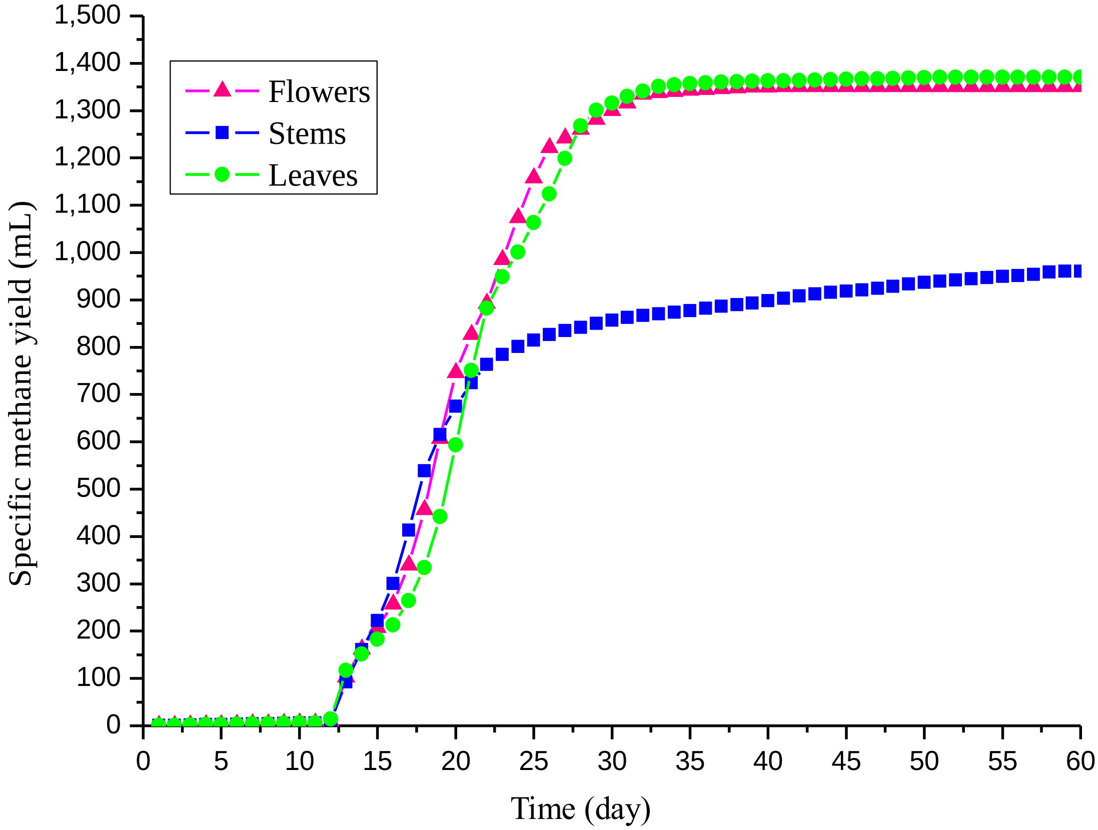

Figure 2. The specific methane yield of the three samples of BSW.

methane yields obtained in the current study conformed to the range of results obtained from other plants and straw (Redzwan and Banks, 2004; Donoso et al., 2010) (Figures 4 to 6).

The maximum daily methane production peak of flowers (154 mL) and leaves (151 mL) occurred on the 23rd day; however that of stems (120 mL) was on the 17rd day (Figure 3). The achieved cumulative methane yield of stems (120 mL) was much lower than that of flowers (154 mL) or leaves (151 mL). This could be primarily due to the fact that stems contain significant amounts of complex lignocellulose structure which limits the anaerobic biodegradability.

The parameters obtained in the optimization process are summarized in Table 2. There was an overall agreement between the models and the experimental data. Among the performance models, the best fit was obtained using the Gompterz equation, which achieved the highest regression of coefficients in all cases (> 0.993). In case of BSW flowers, methane production potential (P, in mL) was ranked as follows: transference function (1388)> modified Gompertz equation (1355)> logistic function (1351). Maximum specific biogas production rate (R_m, in mL) of flowers was ranked as follows: logistic function (287.6)>Gompertz equation (266)> transference function (141.2). For BSW leaves, biogas production potential and maximum specific biogas production rate in different models were almost same as those of the flowers (Table 2). Similarly, biogas production potential (P, mL) and maximum specific biogas production rate (R_m, in mL/(g·VS·day) of stems ranked as follows: transference function (929.4)> modified Gompertz equa-tion (907)> logistic function (903.2) for P; and logistic function (244.8) > modified Gompertz equation (241.7)> transference function (127.4) for R_m.

The difference in lag time (λ) was negligible in the cases of the logistic function and modified Gompertz equation, varying from 0.1 to 0.3 days for flowers, leaves and stems. Calculated lag time difference was found to be less than 1 day for transference function, lag time ranging between 2.062 to 2.379 for flowers, leaves and stems. However, the lag time of 2 to 5 days were observed among three models, because the readily biodegradable components of each feedstock were broken down at different rates (Table 2). Furthermore, the correlation coefficients (R^2) of nonlinear analysis for flowers, leaves and stems were above 0.990 in all models except for the transference equation in which it ranged from 0.906 to 0.935. The best consistency was obtained with the modified Gompertz equation.

All the models consisted of the experimental data with regression coefficients above 0.90, however among the

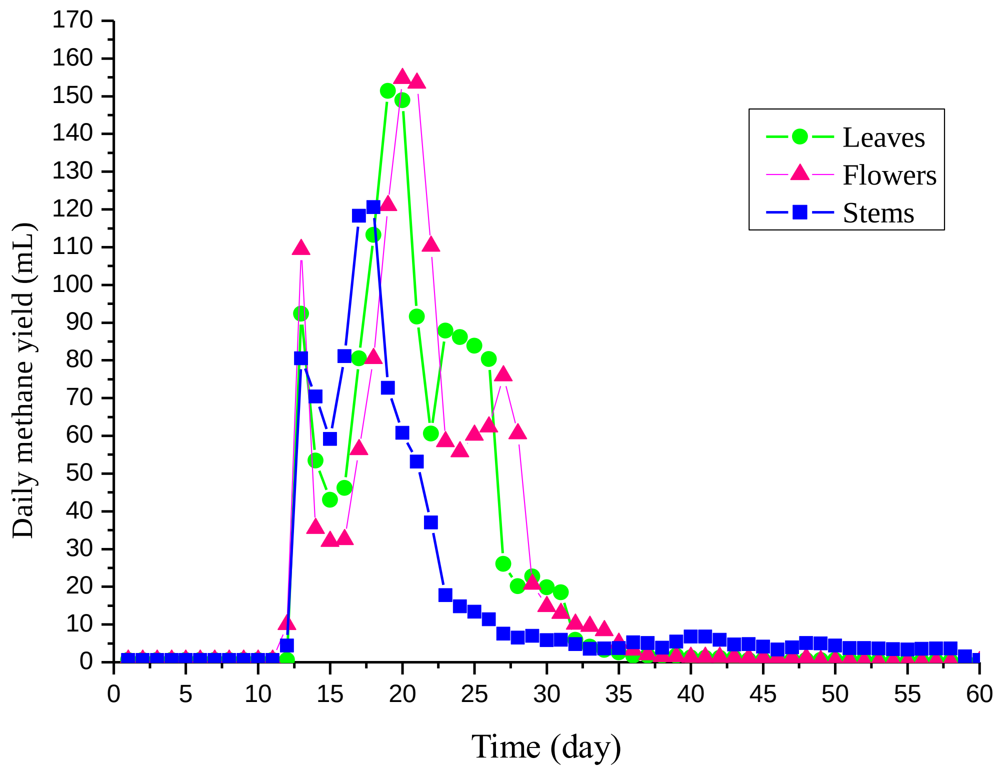

Figure 3. The daily methane yield of the three samples of BSW.

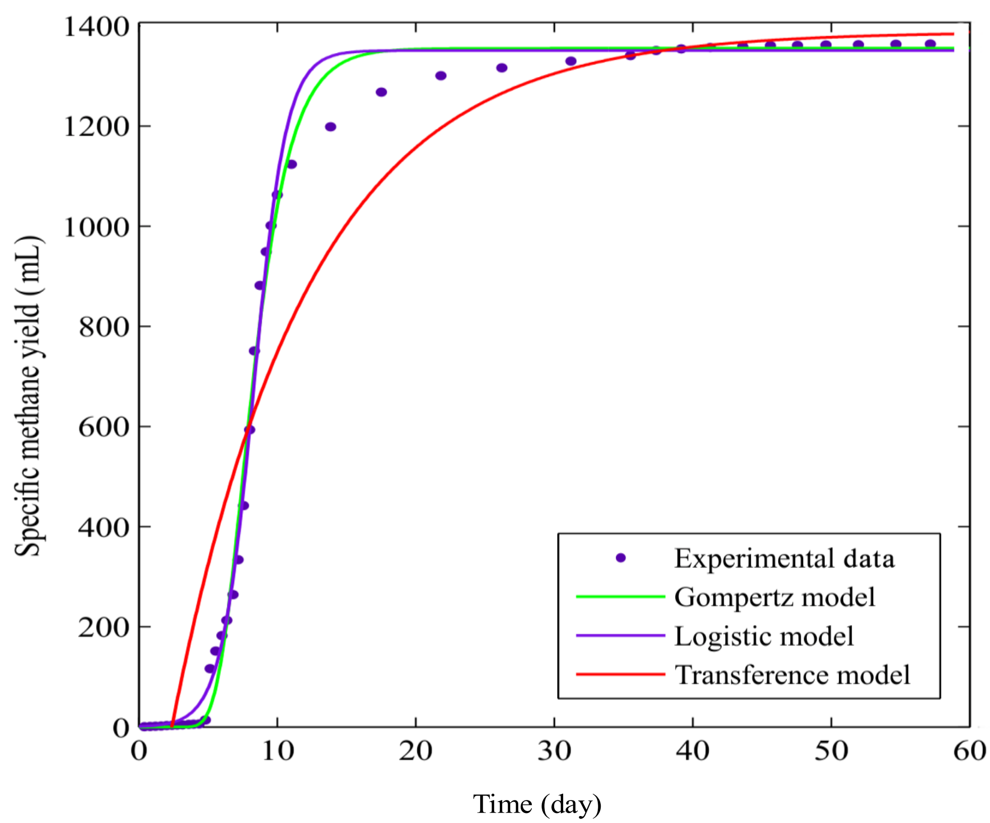

Figure 4. Model fit with methane yield of BSW flowers.

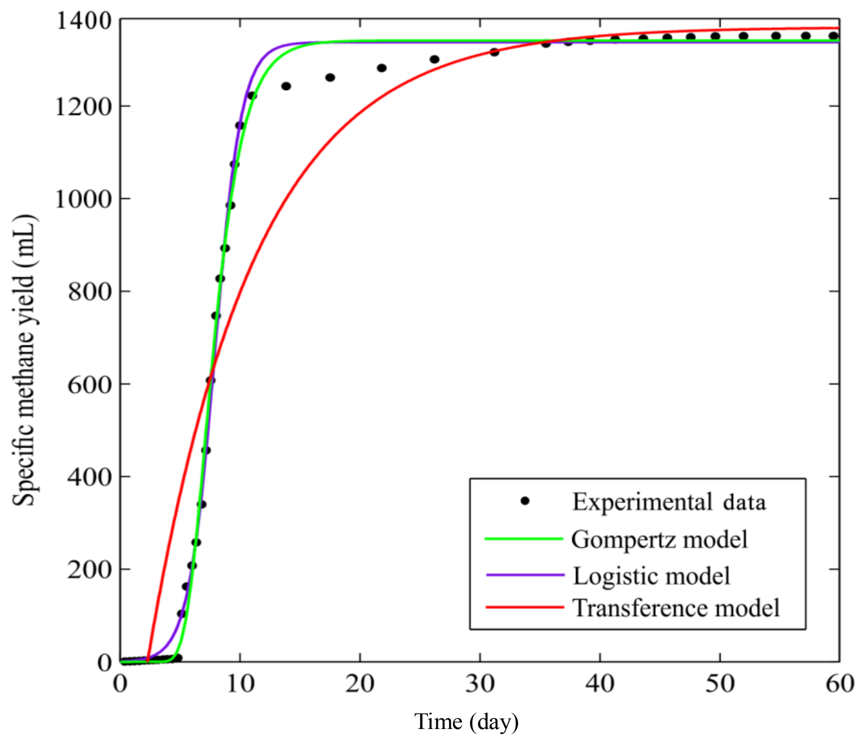

Figure 5. Model fit with methane yield of BSW leaves.

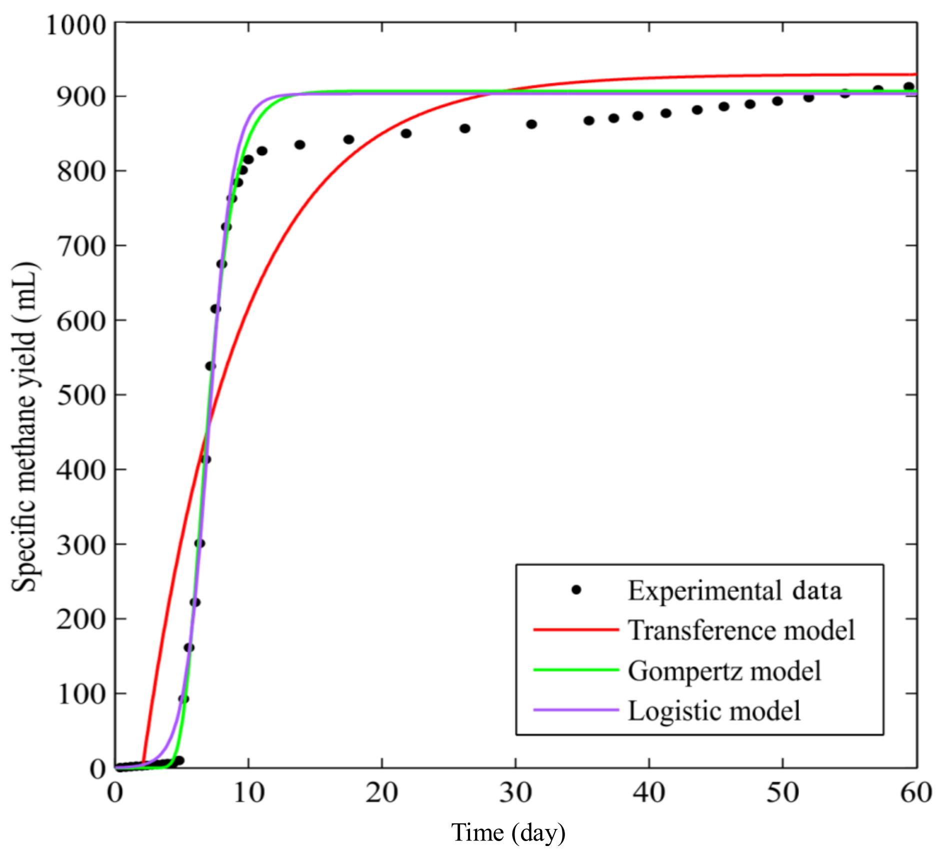

Figure 6. Model fit with methane yield of BSW stems.

Table 2. Parameters and conformance to the evaluated models.

Sample	Model	P(mL)	R_m(mL/(g·VS)	λ(day)	R^2
Flowers	Gompertz equation	1355	266.1	5.635	0.9967
	Logistic function	1351	287	5.934	0.9964
	Transference function	1388	141.2	2.379	0.9359
Leaves	Gompertz equation	1341	289.3	5.445	0.9982
	Logistic function	1338	301.2	5.674	0.9979
	Transference function	1370	155	2.285	0.9261
Stems	Gompertz equation	907	241.7	5.012	0.9936
	Logistic function	903.2	244.8	5.156	0.9916
	Transference function	929.4	127.4	2.062	0.9066

models; the modified Gompertz equation presented the best agreement. A comparison between the modified Gompertz, logistic, and Richards's models was performed by Altas (2009), who fit these models to biogas production from granular sludge to describe the deactivation of anaerobic microbial activity by heavy metals.

Economic benefit analysis

On one hand, AD is known as a more environmental friendly and energy saving approach for organic waste treatment than other disposal methods like landfilling, incineration and composting (Hosseini et al., 2014). On the other hand, this experimental study was carried out on the purpose of feasibility evaluation towards heat and power generation in large-scale anaerobic digestion system.

Compared with other similar fermentation raw material, the methane production potential of *B. spectabilis* is better (Luo et al., 2013). In view of the fact that *B. spectabilis* waste can produce biogas through anaerobic digestion approach, anaerobic digestion is not only one of the feasible ways to treat *B. spectabilis* waste, but also an ideal method with high energy efficiency.

Additionally, our researching team is going to implement further studies on economic benefits analysis of *B. spectabilis*'s biogas engineering. What's more, a new-installed biogas project with *B. spectabilisas* main fermentative material is about the set-up at present.

Conclusions

1. Methane gas production peaks ranged from the 13^{th} to the 27^{th} day; the maximum rates of biogas production occurred during this period. BSW flowers, leaves and stems were observed to produce 65.95, 56.29 and 18.8 mL/(g·VS), respectively. BSW is an excellent feedstock for AD. The results obtained from this experiment can be useful for the further development of BSW biogas projects in Kunming City.

2. A significant difference between the models was observed for the value of maximum methane production rate. Among the models, the modified Gompertz equation showed better consistency with the experimental data than the transference model or logistic model.

Conflict of interests

The authors did not declare any conflict of interest.

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