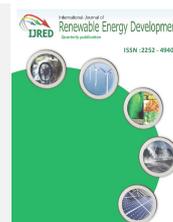




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Research Article

# The Utilization of Water Hyacinth for Biogas Production in a Plug Flow Anaerobic Digester

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**ABSTRACT.** Water hyacinth (*Eichhornia crassipes*) causes ecological and economic problems because it grows very fast and quickly consumes nutrients and oxygen in water bodies, affecting both the flora and fauna; besides, it can form blockages in the waterways, hindering fishing and boat use. However, this plant contains bioactive compounds that can be used to produce biofuels. This study investigated the effect of various substrates as feedstock for biogas production. A 125-l plug-flow anaerobic digester was utilized and the hydraulic retention time was 14 days; cow dung was inoculated into water hyacinth at a 2:1 mass ratio over 7 days. The maximum biogas yield, achieved using a mixture of natural water hyacinth and water (NWH-W), was 0.398 l/g volatile solids (VS). The cow dung/water (CD-W), hydrothermally pretreated water hyacinth/digestate, and hydrothermally pretreated water hyacinth/water (TWH-W) mixtures reached biogas yields of 0.239, 0.2198, and 0.115 l/g VS, respectively. The NWH-W composition was 70.57% CH<sub>4</sub>, 12.26% CO<sub>2</sub>, 1.32% H<sub>2</sub>S, and 0.65% NH<sub>3</sub>. The modified Gompertz kinetic model provided data satisfactorily compatible with the experimental one to determine the biogas production from various substrates. TWH-W and NWH-W achieved, respectively, the shortest and (6.561 days) and the longest (7.281 days) lag phase, the lowest (0.133 (l/g VS)/day) and the highest (0.446 (l/g VS)/day) biogas production rate, and the maximum and (15.719 l/g VS) and minimum (4.454 l/g VS) biogas yield potential.

**Keywords:** Anaerobic digester, biogas, cow dung, hydraulic retention time, water hyacinth.

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## 1. Introduction

Limited petroleum reservoirs and environmental issues have made several countries worldwide start turning to the production and/or utilization of biofuels. Indonesia is a potential producer of raw materials for fuels alternative to petroleum; with its increasing population growth, the demand for energy and fuels is also rising, while the sources of fossil fuels are shrinking. Besides, using fossil fuels can induce climate change and greenhouse gas emissions, especially the carbon dioxide released when burning products. Energy supply is paramount for the economic development of a country; energy plays an important role and cannot be separated from human life, especially now that all the human activities are very dependent on it. Energy is used for supporting various devices, including lighting equipment, household appliances, and industrial machinery. Climate change can

result from technological advances and global warming, successively promoting the utilization of renewable energies. Therefore, it is time to switch to alternative energy obtained from renewable raw materials such as plant biomass. Biogas is produced by the fermented products of organic waste decomposed by microorganisms via anaerobic digestion (Ichsan *et al* 2014; Rico *et al.*, 2014), which is a widely used technology for this purpose. In this process, various microorganisms play active roles through complex tissue processes and interact with each other to degrade complex organic compounds (e.g., carbohydrates, fats, and proteins) into methane and carbon dioxide (Rao *et al.*, 2010; Soeprijanto *et al.*, 2019); this microbiological process is conducted in a digester. Various microorganisms participate in this anaerobic biodegradation process and produce two main final products: energy-rich biogas and nutrient-rich digestate (Soeprijanto, 2019). Several metabolic reactions, including

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hydrolysis, acidogenesis, acetogenesis, and methanogenesis, are involved in the anaerobic digestion (Soeprijanto *et al.*, 2019). Among these microorganisms, *Actinomyces*, *Thermomonospora*, *Ralstonia*, and *Shewanella* bacteria are key for breaking down organic waste into volatile fatty acids, while *Methanosarcina* and *Methanobacteria* species mainly produce methane (Ike *et al.* 2010). Thus, the presence of *Methanosarcina thermophila*, *Methanoculleus thermophilus*, and *Methanobacterium formicicum* is crucial for the anaerobic digestion (Charles *et al.*, 2009). Besides hydrogenotrophic species, especially *Methanobrevibacter sp.*, *M. formicicum*, and *Methanosarcina sp.* are active in synthesizing methane (Trzcinski *et al.*, 2010). The methane production yield is also directly dependent on the number of hydrogenotrophic species involved (Trzcinski *et al.*, 2010). However, high concentrations of organic acids, such as acetic acid (>5000 mg/L) and butyric acid (>3000 mg/L), in biodigesters inhibit the growth of such microorganisms and, thus, decrease the production of energy-rich compounds (Kim *et al.*, 2008).

The organic waste used for biogas production allows low investment and production costs compared to other renewable energy sources, such as solar cells, windmills, and biomass resources (Rao *et al.*, 2010). Aquatic plants like water hyacinth (*Eichhornia crassipes*) that are rich in lignocellulosic and other bioactive compounds are favorable feedstock for biofuel production and high biomass yield. Water hyacinth is a floating plant that grows in marshes, lakes, water reservoirs, and rivers, where the water flow is quite; due to its fast and uncontrolled growth, it is considered a weed and can damage the aquatic ecosystem due to eutrophication. This often causes problems, namely, it increases evapotranspiration, because its wide leaves cover the entire water surface, potentially clogging irrigation systems and hindering the water traffic in those areas where people still rely on and move along rivers. Moreover, the oxygen solubility in the water is reduced by the consequent sunlight obstruction, decreasing the biota population, altering the water chemistry, and inducing environmental pollution (Sharma *et al.*, 2016).

However, since water hyacinth contains organic material (61.8%–88.86%), nitrogen (1.01%–2.29%), and organic carbon (33.84%–51.54%), with a C/N ratio of 22.5–33.46 (22.5%–35.48%), its biomass is a potential raw material for the development of biofuels such as bioethanol and biogas (Clementson *et al.*, 2016; Longjan and Dehouche, 2017; Mathew *et al.*, 2014). Moreover, *E. crassipes* has a low lignin content and its other components, that is, cellulose and hemicellulose, can be easily hydrolyzed to sugar. Thus, large amounts of water hyacinth biomass are available for biofuel production; besides, there is no competition between water hyacinth and the land plants used in the cultivation of food crops (Bhattacharya and Kumar, 2010).

In 2010, O'Sullivan *et al.* demonstrated the potentiality of water hyacinth for biogas production, reporting a production yield of 0.2–0.4 l/g volatile solids (VS). However, Vaidyanathan *et al.* (1985) had achieved a higher CH<sub>4</sub> yield obtained (0.430 l/g VS) by using water hyacinth during anaerobic digestion in batch mode. O'Sullivan *et al.* (2010) also compared the feedstocks of water hyacinth, *Salvinia*, and *Cabomba* plants, which were heat-treated via drying and nutrient addition on

biogas production using a test of biochemical methane potential and pilot plant studies. Water hyacinth and the *Cabomba* plants were easily degraded, reaching a biogas production yield of 0.267 and 0.221 l/g VS, respectively, while the *Salvinia* biomass exhibited a yield of only 0.155 l/g VS. This study demonstrated that the biogas production was detrimental by drying for all three feedstocks. Navarro *et al.* (2012) focused on the effluent of the lemon industry wastewater treatment and the biogas production by water hyacinth, obtaining a maximum yield of 0.87 l/g VS in anaerobic digestion with a hydraulic retention time (HRT) of 16 days.

The present study investigated the biogas production via continuous anaerobic digestion; as the feedstock, water hyacinth plants were from the swamp water at the Institut Teknologi Sepuluh Nopember (ITS) in Surabaya (Indonesia). Because the use of fossil fuels produces gas such as CO<sub>2</sub>, SO<sub>2</sub>, and NO<sub>x</sub>, causing air pollution and adverse impacts on the environment and human health, environmental sustainability is an important aspect to consider.

This work aimed to evaluate the effect of using natural and hydrothermally pretreated water hyacinth (NWH and TWH) for biogas production in a continuous plug-flow anaerobic digester and to optimize the corresponding modified Gompertz kinetic model.

## 2. Materials and methods

### 2.1 Materials

Cow dung was used as the microbial source for decomposing the organic matter contained in water hyacinth, to produce biogas; it was obtained from slaughterhouses in Pegirian, Surabaya. Its total solid (TS) and VS concentrations were 15.51% and 84.10%, respectively. Water hyacinth, serving as the carbon source, was taken from ponds located at the ITS. Acetone (99.5%, Smart Lab), sulphuric acid (95%–97%, Sigma-Aldrich), sodium hydroxide (99%, Merck) were all used at their analytical grade.

### 2.2 Methods

#### 2.2.1 Pretreatment of raw materials

The raw materials were mechanically pretreated by reducing their particle size, which increased their specific surface area. After being collected, water hyacinth was cut and ground to obtain a particle diameter of about 0.5 cm (Fig. 1); when not used directly, the residues were stored in a refrigerator at 4 °C for later utilization.

Then, hydrothermal pretreatment was conducted in an autoclave (8-mm-thick stainless steel walls, 20-cm diameter, 50-cm height, and 15-l total volume) with water at 100°C for 1–1.5 h. Next, the solid fraction was separated and washed with tap water, followed by the addition of other tap water until reaching a volume of 9 l; meanwhile, the liquid fraction was analyzed to determine the sugar byproducts of this hydrothermal process.

Fig. 2 schematizes a plug-flow anaerobic digester. The digester used in this study was made of stainless steel, its effective volume was 125 l, and it was equipped with a flat stirrer to obtain a homogeneous slurry and

prevent biogas from being trapped in it (Sluiter *et al.*, 2008). It was constructed for continuous mode; the feedstock flow rate was around 9 l/day, at an HRT of approximately 14 days. The process was conducted at room temperature. The thermometer and biogas pipe were located at the top of the digester. A motor was installed to automatically and sequentially move and stop the stirrer for 60 and 30 min, respectively.

First, a certain amount of cow dung, mixed with water in a 1:2 mass ratio, was introduced into the digester. The digestion was left proceeding for several days and biogas production was observed. Next, crushed water hyacinth (3 kg) was suspended in water at a volume of 9 l with a 1:2 mass ratio. Various feedstocks were used in this experiment: the 1:2 mixture of fresh cow dung and water (CD-W); the 1:2 mixture hydrothermally pretreated water hyacinth (TWH) and water (TWH-W), where the water hyacinth was cut into small pieces and pretreated at 100 °C for 30 min and successively blended; a mixture of TWH and digestate (TWH-D); a 1:2 mixture of NWH and water (NWH-W). The biogas production was evaluated in terms of volume (ml, l) and concentrations (%) of CH<sub>4</sub>, NH<sub>3</sub>, CO<sub>2</sub>, and H<sub>2</sub>S.



(a)



(b)

Fig. 1 (a) Natural and (d) ground water hyacinth, used for biogas production.

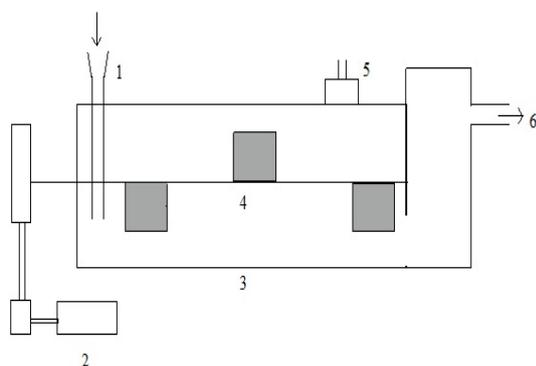


Fig. 2 Diagram of a plug-flow anaerobic digester: 1 = influent; 2 = drive motor; 3 = digester; 4 = blade; 5 = biogas pipe; 6 = effluent.

### 2.2.2 Proximate and ultimate analysis

The water content in water hyacinth was determined according to ASTM-D 3173-87 (APHA, AWWA, WPCF, 1995; ASTM-D 3173-87, 2003). The TS, VS, and ash were determined by following the AOAC Standard method (2000), at the beginning of the experiment. The TS consists of VS and fixed solids; the VS is the organic part that breaks down anaerobically (Clesceri *et al.*, 1998; Lin *et al.*, 2010). Cellulose, hemicellulose, extractives, and lignin were determined via proximate analysis (Ayeni *et al.*, 2014, 2015; Naik *et al.*, 2010; Sluiter *et al.*, 2008). The total organic carbon (TOC) was calculated as VS/1.8. Carbon was determined with the combustion method in a muffle furnace, where the plant material was burned at 550 °C for 4 h (Clesceri *et al.*, 1998).

### 2.2.3 Biogas analysis

The biogas produced was collected in a plastic tube and its volume was estimated based on the downward displacement of water. The gas analysis of CH<sub>4</sub>, H<sub>2</sub>S, NH<sub>3</sub>, and CO<sub>2</sub> contents in the produced biogas, were measured using a gas chromatograph (Shimadzu GC 2010) equipped with a thermal conductivity detector.

### 2.2.4 Modified Gompertz kinetic model of biogas production

A kinetic model was derived from the modified Gompertz one, which is commonly used to simulate some important kinetic parameters when utilizing an anaerobic digester. The model parameters were estimated with a nonlinear curve fitting tool obtained by optimization. This modified Gompertz kinetic model has already been used for the successful prediction of maximized biogas production for the perfect lag time (Budiyono *et al.*, 2014; Lo *et al.*, 2010; Nopharatana *et al.*, 2007; Yusuf *et al.*, 2011). This model is as follows:

$$P = Y_p \cdot \exp \left\{ -\exp \left[ \frac{\mu_m \cdot e}{Y_p} (\lambda - t) + 1 \right] \right\} \quad (1)$$

where:

- $P$  is cumulative biogas production (l/g VS) at any time ( $t$ ),
- $Y_p$  is biogas yield potential (l/g VS),
- $\mu_m$  is the maximum biogas production rate (l/g-VS/day),
- $\lambda$  is the duration of lag phase (day),
- $t$  is time at which cumulative biogas production (day) and
- $e$  is mathematical constant (2.718282).

### 2.2.5 Statistical analysis data

The analysis of variance was performed at the significance when  $p \leq 0.05$  for statistical tests. Single and multiple variable regression analyses were conducted using the SPSS Statistics 17 software. The experimental data were statistically simulated via nonlinear regression to determine all the parameters of the modified Gompertz kinetic models ( $Y_p$ ,  $\mu_m$ , and  $\lambda$ ) by using the SPSS Statistics 17 software.

### 2.2.6 Fourier transform infrared spectroscopy (FTIR)

The changes in the chemical composition of the water hyacinth fibers before and after digestion were investigated via FTIR. The samples were directly loaded on a specific cab and scanned by a Nicolet iS10 FT-IR Spectrometer (Thermo Fisher Scientific) operated in the transmission mode; the spectra were measured in the wavenumber range of 400–4000  $\text{cm}^{-1}$  at the resolution of 4  $\text{cm}^{-1}$ , with 40 scans for each sample to increase the accuracy.

## 3. Results and discussion

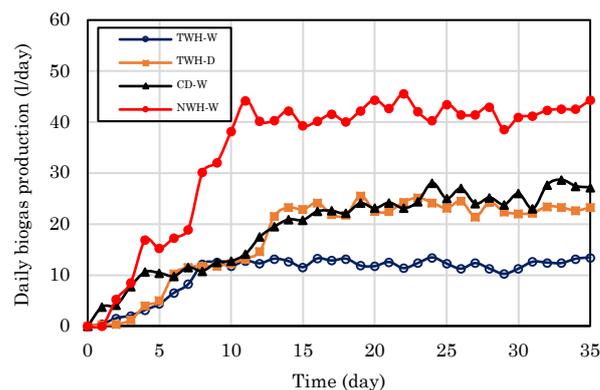
### 3.1. Physical-chemical characteristics of water hyacinth

In this study, water hyacinth was used as the feedstock for biogas anaerobic digestion; Table 1 lists its physicochemical properties, which were determined by analyzing the TS, VS, organic carbon, and total nitrogen contents. The moisture content was 94.35%, consistently with what reported by Patil *et al.* (2011, 2012).

The biogas production from organic substrates mainly depends on the organic fraction degraded to  $\text{CH}_4$  and  $\text{CO}_2$ . The carbon/nitrogen ratio (C/N) is an important factor influencing the biogas production; it is calculated by dividing TOC to total organic nitrogen (TON). In general, the appropriate C/N range is 20–30 for anaerobic digestion. However, in the present study, its value was 12.42, and a great amount of biogas was produced as expected via anaerobic digestion. Besides, the average TS content in the digestate was approximately 5.76% (w/w). Therefore, during the operation, about 75% of TS from the feedstock was converted into biogas, while the average conversion of VS was around 81.45%. Kumar *et al.* (2010) reported that the C/N of food and green waste used as feedstock is 19.6, resulting in effective anaerobic digestion. Mathew *et al.* (2014) used a 2:1 cow dung/water hyacinth mixture in the batch mode over 60 days; they observed a C/N of about 29.23 for the plant. Matheri *et al.* (2017) stated that a C/N of 25 is also suitable for municipal solid waste. The biogas production obtained via anaerobic digestion over 14 days was 0.385 l/g VS. However, in the mono-digestion of corn stover and chicken manure, the observed C/N values are 63.2 and 10.1, respectively, while those in their corresponding co-digestion are 17.4 and 27.3.

**Table 1**  
Physicochemical characteristics of water hyacinth (dry base).

Parameters	Values
Moisture (%)	94.35
Total Solids, TS (%)	5.65
Volatile Solids, VS (%TS)	70 – 85
Total Organic Carbon, TOC (%)	39.14
Total Organic Nitrogen, TON (%)	3.15
Ratio of C/N	12.42
Extractives (%)	4.8
Cellulose (%)	38.1
Hemicellulose (%)	30.2
Lignin (%)	23.3
Ash (%)	5.16



**Fig. 3** Biogas production from various feedstocks: hydrothermally pretreated water hyacinth (TWH) mixed with water (TWH-W), TWH/digestate (TWH-D), natural water hyacinth/water (NWH-W), and cow dung/water (CD-W).

### 3.2 Biogas production

#### 3.2.1 Daily biogas production

The continuous anaerobic digestion was divided into two stages: start up and stable operation. The HRT was adjusted to approximately 14 days and different feedstocks were used (Fig. 3), observing a relationship between substrate composition and biogas production. A constant biogas production per day indicated that the process, in continuous mode, has reached steady-state conditions. The biogas production from TWH-W increased significantly up to 13.2 l/day during the first eight days and, then, remained relatively constant until the 35<sup>th</sup> day, with an average biogas production per day of 12.05 l/day. As regards TWH-D, the biogas production increased greatly up to 21.55 l/day during the first 14 days and, successively, was relatively stable with an average value of 23.08 l/day; this indicates a higher biogas yield than with TWH-W. Therefore, using a water hyacinth mixture and digesting from the digester effluent could effectively improve the carbon sources and nutrients required by microorganisms to degrade water hyacinth and generate biogas. Moreover, the NWH-W feedstock exhibited even better results, with a daily biogas production increasing during the first ten days up to 38.24 l/day and a successive stable value of 41.77 l/day.

As for CD-W, the biogas production increased until reaching 22.60 l/day on the 17<sup>th</sup> and, then, was relatively constant with an average value of 25.09 l/day. This result, which is lower than that obtained with NWH-W, contradicts what reported by Pachaiyappan *et al.* (2014), which observed methane and carbon dioxide productions of 45% and 70%, respectively. Cow dung is generally degraded more slowly than other organic materials because it contains residual lignin complexes deriving from the animal feedstock that are highly resistant to anaerobic digestion (Abdeshahian *et al.*, 2016; Monteiro *et al.*, 2011). This is why the biogas production from cow dung is usually lower than from other organic sources. Besides, the results of the present study indicate biogas production yields of 0.115, 0.2198, 0.398, and 0.239 l/g VS from TWH-W, TWH-D, NWH-W, and CD-W, respectively; this well agrees with previous results obtained using water hyacinth as the feedstock. Patil *et al.* (2011) performed the anaerobic digestion of natural water hyacinth with different amounts of water, observing a

maximum biogas yield of 0.245 l/g VS when using water hyacinth slurry in a ratio of 1:4, in the mesophilic temperature range of 30 °C–37 °C for 60 days. Rozy *et al.* (2017) reported a biogas production of 0.045 l/g water hyacinth, 0.3601 l/g TS, and 0.398 l/g VS in optimal conditions within 40 days. O'Sullivan *et al.* (2010) obtained a biogas production potential of 0.2–0.4 l/g VS with water hyacinth. Vaidyanathan *et al.* (1985) reported a higher yield (0.430 l/g VS) through the batch digestion of water hyacinth. Mathew *et al.* (2014) observed a production yield of 0.552 l/g VS from the same plant. Navarro *et al.* (2012) combined the lemon industrial wastewater with water hyacinth in an anaerobic digester, achieving a maximum biogas production of 0.87 l/g TS within 16 days. All the previous results mentioned above were obtained in batch cultures with fresh inoculum each time. However, all these experiments were conducted in a continuous culture. This made the organisms less active in the continuous culture than in the batch one. The results obtained in these studies are in agreement with previous data obtained using food and vegetable waste as the feedstock; when using a continuously stirred tank reactor and a continuous tubular reactor, the production yields were 0.47 and 0.45 l/g VS, respectively, with corresponding VS of 88% and 76% (Mata-Alvarez *et al.*, 1992; Bouallagui *et al.*, 2003).

### 3.2.2 Cumulative biogas production

Fig. 4 illustrates the *P* results for the various biomasses investigated, revealing similar trends for all of them. Within the first few days, the biogas production was quite low. The highest *P* was from NWH-W, with a biogas production of 1229.83 l, s followed by CD-W, TWH-D, and TWH-W with *P* values of 686.10, 628.50, and 370.46 l, respectively. This result can be attributed to the several components present in the natural water hyacinth. Moreover, TWH-W exhibited the lowest production was probably due to the great amount of components degraded and lost during the hydrothermal pretreatment, which resulted in low TS, VS, carbon, and nitrogen contents (Table1).

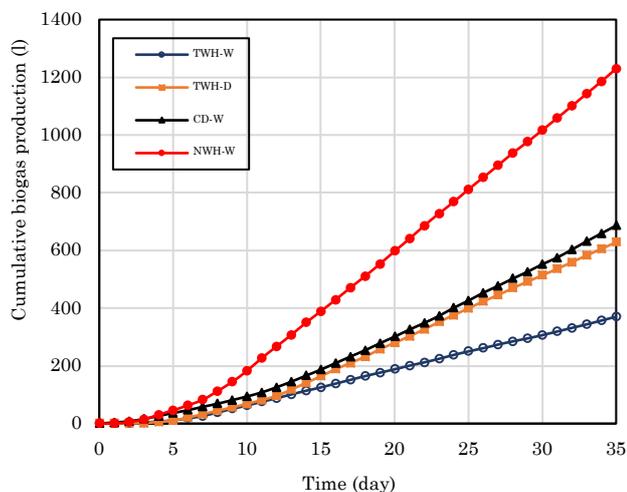


Fig. 4 Cumulative biogas production from different feedstocks: hydrothermally pretreated water hyacinth (TWH) mixed with water (TWH-W), TWH/digestate (TWH-D), natural water hyacinth/water (NWH-W), and cow dung/water (CD-W).

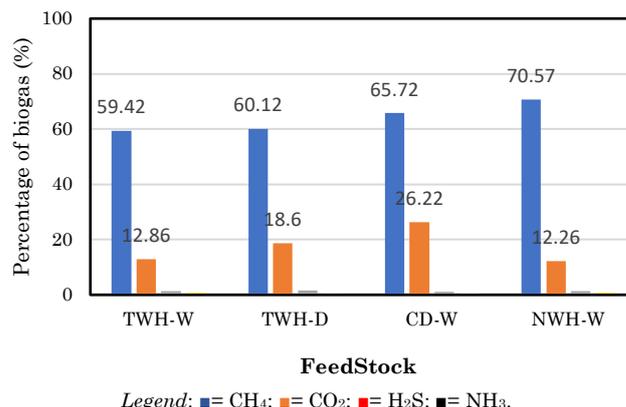


Fig. 5 Composition of the biogas produced from different feedstocks: hydrothermally pretreated water hyacinth (TWH) mixed with water (TWH-W), TWH/digestate (TWH-D), natural water hyacinth/water (NWH-W), and cow dung/water (CD-W).

### 3.2.3 Biogas composition

Fig. 5 compares the biogas composition resulting after the steady-state process with the various feedstocks, revealing a CH<sub>4</sub> content range of 50%–70%, CO<sub>2</sub> (10–30%), H<sub>2</sub>S (1–2%), and NH<sub>3</sub> (0.1–0.2%), respectively. The results revealed that the highest experimental methane content (70.57%) was achieved by digesting NWH-W, then followed by CD-W (65.72%), TWH-D (60.12), and TWH-W (59.42), respectively. Besides, the results of the present study indicate methane production yields of TWH-W, TWH-D, NWH-W, and CD-W were 0.0683, 0.1321, 0.2809, and 0.1571 l CH<sub>4</sub>/g VS, respectively; this well agrees with previous results obtained using water hyacinth as the feedstock. Shah *et al.* (2015) reported the methane produced during that study was in range of 129.7–150.8 l-CH<sub>4</sub>/g VS with water hyacinth. However, Rico *et al.* (2014) performed dry batch anaerobic digestion of food waste in a box-type reactor system, finding the methane production yields of 0.405 l CH<sub>4</sub>/g VS. Paudel *et al.* (2017) obtained a methane yield of 0.67 l CH<sub>4</sub>/g VS through a system operated in HRT of 15 days for 80 days and the methane content during steady state condition was found to be 63%.

### 3.3 Determination of kinetic parameters using modified Gompertz equation

According to this study results, the biogas production depends on the bacterial growth in a continuous anaerobic digester at the start-up stage. The fitness for prediction of *P* was estimated using the modified Gompertz model. Table 2 lists the as-determined kinetic parameters, demonstrating that the modified Gompertz model provided good compatibility in predicting biogas production for all the variables, with a regression coefficient (*R*<sup>2</sup>) of 0.99.

The results of this study were similar to those reported by other authors (Budiyono *et al.*, 2014; Kumar *et al.*, 2018; Nopharatana *et al.*, 2007; Wei *et al.*, 2015). Kumar *et al.* (2018) observed  $\mu_m$ ,  $\lambda$ , and  $Y_p$  values of 0.20 days, 9.47 days, and 6.4265 l, respectively, for a digester at 30 °C. Wei *et al.* (2015) calculated  $\lambda$  values of 2.0–6.6 days for pretreated corn stover and of 10.2 days for the

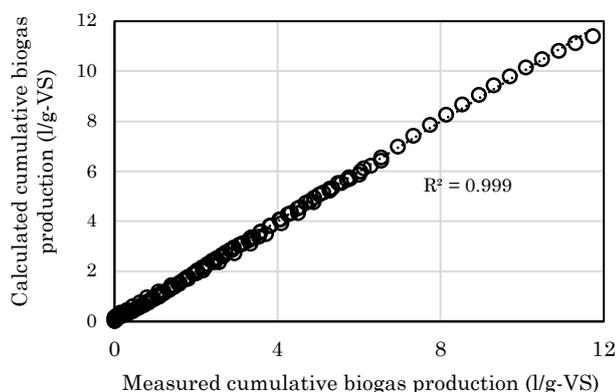
untreated samples. Samuel *et al.* (2017) investigated the methane production from vegetable wastes, obtaining a 374.09 l/kg VS production potential, a maximum production potential of 17.269 (l/kg VS)/day, a lag phase of 3.935 days, and a yield of 353.41 l/kg VS. Opurum *et al.* (2015) mixed a fish pond effluent (FPE) with cow dung (CD) at a ratio of FPE/600 g CD; the highest  $Y_p$  value was 304.10 ml/g VS, but  $\mu_m$  was 4.33 (ml/g VS)/day and  $\lambda$  was 21.22 days when using FPE/400 g CD.

The adequacy of the proposed model was tested via statistical analysis, that is, it determined whether the deviation between measured and calculated values was less than the experimental error of the measurements.

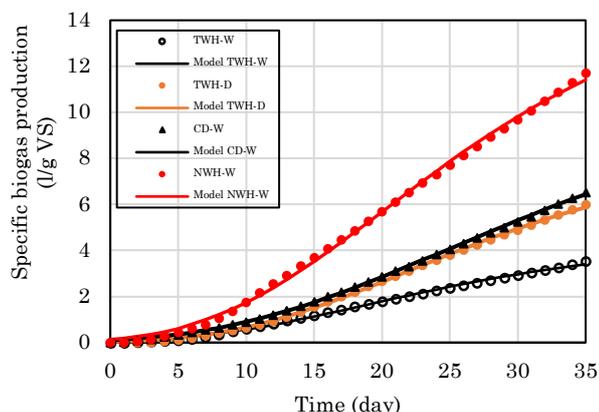
**Table 2**

Kinetic parameters derived using the modified Gompertz model for biogas production.

Substrates	$Y_p$ (l/g-VS)	$\mu_m$ (l/g-VS/day)	$\lambda$ (day)	$R^2$
TWH-W	4.454	0.133	6.561	0.997
TWH-D	8.378	0.243	9.160	0.999
CD-W	10.921	0.250	8.669	0.999
NWH-W	15.719	0.446	7.281	0.998



**Fig. 6** Parity plot for cumulative biogas production.



**Fig. 7** Experimental data and values simulated by the modified Gompertz model for biogas production.

Therefore, repeated measurements should be performed. Since such an experiment could not be performed, yet, the model adequacy could not be verified. Nevertheless, as shown in Fig. 6, there was a good agreement between calculated and measured  $P$  values, which indicates that the model is probably adequate. Moreover, Fig. 7 shows the compatibility between the various experimental and simulated data for biogas production.

### 3.2 FTIR analysis

Water hyacinth contains natural fibers that are primarily composed of cellulose, hemicellulose, and lignin. In this study, the characteristics of natural and digested water hyacinth were investigated via FTIR analysis. The FTIR spectra of this plant generally show many absorption bands in different regions and cannot be accurately interpreted to identify the functional groups; however, they allow the distinction between pretreated and digested water hyacinth. The FTIR results of the natural, pretreated, and digested samples revealed the presence of various chemical compounds (Fig. 8); the wavenumbers of their prominent peaks are summarized in Table 3.

The signal wavenumber attributed to the O–H stretching was similar among the three samples, but its value was lower for the digested one, whose crystalline cellulose was slightly degraded after the digestion process. The C–H stretching band (Dasong and Mizi, 2010; Nur Aimi *et al.*, 2015) was also observed at a lower wavenumber for the digested water hyacinth, indicating its partial degradation. The peak at 1604.11–1632.54  $\text{cm}^{-1}$  was attributed to the carbonyl aldehyde from lignin; in this case, the digested sample exhibited the highest wavenumber, which means that the carbonyl aldehyde was not degraded during the digestion. In contrast, the C–H deformation vibration signal was observed at a higher wavenumber for the natural water hyacinth (1419.53  $\text{cm}^{-1}$ ), suggesting a variation in the carbonyl groups of the acetyl ester from hemicellulose after the digestion. Nevertheless, the peak attributed to the C–C, C–O, and C–OH stretching vibrations in hemicellulose, cellulose, and lignin (Ding *et al.*, 2012) had similar wavenumbers among the three samples, indicating that the crystalline cellulose of water hyacinth was not completely degraded during the digestion. There was an insoluble residue of the crystalline cellulose during the digestion.

Besides, the natural water hyacinth also showed peaks at 2853.08, 1729.90, 1313.63, and 1245.75  $\text{cm}^{-1}$  that were assigned to, respectively, the C–H stretching, acetyl and ester in the carboxyl group chains of the acid p-coumaryl as well as indicating the presence of lignin and hemicellulose, feruloyl and p-coumaryl groups in lignin and/or the C–O stretching of hemicellulose (Ghali *et al.* 2012; Ludena *et al.* 2011; Thiripura & Ramesh, 2012), the C–O–C oscillation of hemicellulose in the anomeric region (Abraal *et al.*, 2014), and the C–N stretching with amine. All these peaks disappeared after the digestion process, probably due to the removal of hemicellulose and lignin (Ding *et al.*, 2012; Sundari & Ramesh, 2012). Moreover, the digested sample showed a new peak at 1538.38  $\text{cm}^{-1}$ , which was attributed to the C=C stretching of the aromatic rings of lignin; this peak was not observed in the natural water hyacinth because of the partial removal of lignin (Sundari & Ramesh, 2012).

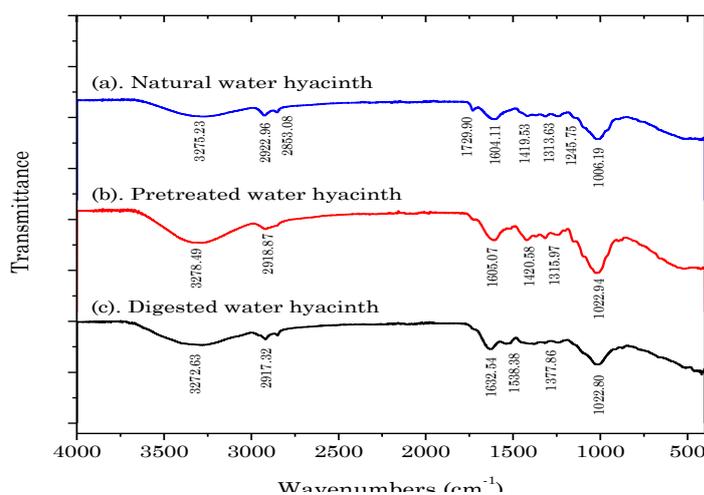


Fig. 8 Fourier-transform infrared spectra of various water hyacinth samples.

Table 3

Functional groups associated with the wavenumbers of the FTIR peaks for the different water hyacinth samples.

Functional group	Wavenumber (cm <sup>-1</sup> )		
	Water hyacinth natural	Water hyacinth pretreated	Water hyacinth digested
-C-C- and -CN stretching	1006.19	1022.94	1022.80
Phenolic OH and ether group; C-N stretching with amine	1245.75	-	-
C-H deformation vibration (asymmetric)	1313.63	1315.97	-
N-alkyl ted aromatic amines, C-H bend alkanes	1419.53	1420.58	1377.86
Aromatic ring vibration, C=C group on the aromatic ring of lignin, N-O asymmetric stretch nitro compounds; N=O Stretch	-	-	1538.38
C=C stretch (Medium); N=O Stretch; C-C=C Symmetric Stretch	1604.11	1605.07	1632.54
C=O stretch aldehydes, saturated aliphatic; C=O stretch (Strong); C=O Stretch	1729.90	-	-
C-H stretching (stretching vibration); C-H stretch alkanes; H-C-H Asymmetric & Symmetric stretch	2853.08	-	-
C-H stretching (stretching vibration), C-H stretch alkanes	2922.96	2918.87	2917.32
O-H stretching, O-H stretching vibrations; hydrogen-bonded O-H Stretch; N-H Stretch	3275.23	3278.49	3272.63

## 6. Conclusion

Water hyacinth is a promising feedstock for producing alternative energy in the form of biogas. An experiment was conducted using an anaerobic digester with an HRT of 14 days. The results showed that the water hyacinth composition influences the biogas production. During 35 days, the NWH-W feedstock achieved the highest cumulative biogas production (1229.83 l), followed by CD-W (686.10 l), TWH-D (628.50 l), and TWH-W (370.46 l); it also exhibited the highest maximum production yield per day (0.398 l/g VS), followed again by CD-W (0.239 l/g VS), TWH-D (0.2198 l/g VS), and TWH-W (0.115 l/g VS). The NWH-W composition was as follows: 70.57% CH<sub>4</sub>, 12.26% CO<sub>2</sub>, 1.32% H<sub>2</sub>S, and 0.65% NH<sub>3</sub>. The modified Gompertz kinetic model provided satisfactory compatibility with the experimental data to determine kinetic parameters and

effectively predicted the biogas production from various substrates based on water hyacinth under certain conditions. TWH-W and NWH-W exhibited the shortest (6.561 days) and the longest (7.281 days) lag phase, respectively, and also the lowest (0.133 l/g VS/day) and the highest (0.446 l/g VS/day) biogas production rate, correspondingly, as well as the minimum (4.454 l/g VS) and the maximum (15.719 l/g VS) biogas yield potential.

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