https://dx.doi.org/10.4314/ijs.v20i3.18

COMPARATIVE EVALUATION AND KINETICS OF BIOGAS YIELD FROM DUCKWEED (*LEMNA MINOR*) CO-DIGESTED WITH WATER HYACINTH (*EICHHORNIA CRASSIPES*)

Ogunwande, G.A.[a,1], **Adanikin, B.A.**[b] **and Adesanwo, O.O.**[c]

[a]Department of Agricultural and Environmental Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria. E-mail: gbolawande@gmail.com; gbolawande@oauife.edu.ng. Tel.: +234 803 4007128

[b]Institute of Ecology and Environmental Studies, Obafemi Awolowo University, Ile-Ife, Nigeria

[c]Department of Soil Science and Land Resources Management, Obafemi Awolowo University, Ile-Ife, Nigeria

[1]Corresponding author's e-mail: gbolawande@gmail.com; gbolawande@oauife.edu.ng. Tel.: +234 8034007128

(Received: 26th January, 2018; Accepted: 24th September, 2018)

ABSTRACT

Anaerobic co-digestion of duckweed (DW) with water hyacinth (WH) at five DW: WH ratios (1:0, 7:3, 1:1, 3:7 and 0:1 w: w dry basis) was carried out with a view to comparing and evaluating the effect on biogas yield. Fixed quantity of cow dung slurry was added to each treatment as inoculum to seed the digesters before digestion for seventeen weeks in batch type digesters. Biodegradation and maximum biogas yield models based on first-order kinetics were fitted to the experimental biogas yields to describe the cumulative and predict maximum biogas yields, respectively from each treatment. The results indicated that DW was viable for biogas production and more prolific than WH. Co-digestion did not affect ($p > 0.05$) temperature and pH but affected ($p \leq 0.05$) total bacterial count and biogas yield. The high R^2 values obtained from the biodegradation model fit showed that the model described the experimental yields satisfactorily. Furthermore, the high R^2 values and percentages of predicted maximum yield/observed maximum yield showed that the maximum biogas yield model predicted the maximum yields satisfactorily. The study concluded that co-digestion of DW and WH was best at ratio 7:3 while ratio 1:1 was the best described and predicted by the biodegradation and maximum biogas yield models.

INTRODUCTION

Duckweed (DW) (*Lemna minor*) and water hyacinth (WH) (*Eichhornia crassipes*) are free floating aquatic plants that can live and reproduce freely on the surface of fresh waters or can be anchored in mud. Duckweed is small and fragile while water hyacinth is long and spongy with bulbous stalks. When conditions are ideal, in terms of water temperature, pH, incident light and nutrient concentrations, DW compete in terms of biomass production with the most vigorous photosynthetic terrestrial plants doubling their biomass in between 16 h and 2 d, depending on conditions. DW and WH are considered some of the world's worst aquatic weeds as they infests rivers, dams, lakes and irrigation channels on every continent.

However, they have received research attention because of their great potential to remove mineral contaminants from waste waters emanating from sewage works, intensive animal industries or from intensive irrigated crop production (Leng *et al.*, 1995; Narayana and Parveez, 2000; Singhal and Rai, 2003; Zhao *et al.*, 2014) and as a feedstock to animals and fish to complement diets and largely to provide a protein of high biological value (Polprasert *et al.*, 1994; Leng *et al.*, 1995; Kusina *et al.*, 1999). In addition, WH has been very well researched and found to be prolific in biogas production (Singhal and Rai, 2003; Almoustapha *et al.*, 2009; Sullivan *et al.*, 2010; Patil *et al.*, 2012).

For years, researchers have been trying to commercialize DW as a viable source of bioenergy for the production of ethanol, biodiesel, natural gas and steam-generated electricity. Recently, studies on the use of DW for biogas production (Clark *et al.*, 2007; Triscari *et al.*, 2009; Strom, 2010; Gaur *et al.*, 2017; Tonon *et al.*, 2017) have been gaining prominence. However, despite these efforts, there is still a dearth of literature concerning the effective co-digestion of DW for biogas production. This study therefore aimed at digesting DW to evaluate the biogas yield and co-digesting DW and WH to compare and evaluate the effect on biogas yield. Furthermore, an organic matter biodegradation model and a maximum biogas yield model based on first-order kinetics were fitted to the biogas yield data to describe the process response and estimate maximum biogas yield attainable, respectively.

MATERIALS AND METHODS

Materials

The anaerobic experiment was conducted at the Department of Agricultural and Environmental Engineering of the Obafemi Awolowo University, Ile-Ife, Nigeria. Fresh cow dung was collected from the University Teaching and Research Farm while duckweed (DW) and water hyacinth (WH) were harvested within 24 h from a fish pond and a lake, respectively in Ile-Ife town.

Analytical Procedure

The feedstocks' samples were analysed for total solids content (oven dried at 105 °C for 24 h); volatile solids (VS) content (ashing of TS at 550 °C for 5 h); total nitrogen (regular-Kjeldahl method; Bremner, 1996); pH (1:10 w/v sample: water extract, using a digital pH meter). The total carbon (TC) content was estimated from the ash content according to the formula by Mercer and Rose (1968):

$$TC\,(\%) = [100 - Ash\,(\%)]/1.8 \qquad (1)$$

Total bacterial count of the substrates was analysed using the pour plate technique according to Hunter-Cerena *et al.* (1986).

Experimental Set up

The experimental set up comprised of digesters, water tanks and water collectors. The digesters were adapted using cube-shaped 25 dm^3 plastic kegs. The kegs were positioned to give surface area (dm^2) and height (dm) dimensions of 2.50 × 4.65 and 2.15, respectively. A drain plug was fitted at the base of each digester for collection of samples for pH and bacterial count analysis. Each digester had a digital thermometer probe fitted to it for temperature measurement. Similarly, the water tanks and water collectors were adapted using 10 dm^3 and 5 dm^3 rectangular plastic kegs, respectively. Rubber hose was used to connect each digester to the water tank and the water tank to the water collector.

Feedstocks Preparation

The roots, stems and leaves of the plants were all digested. Duckweed had its original size < 6 mm of sieve size while WH was cut into < 6 mm sieve size for effective digestion. The plants were mixed at DW: WH (w:w dry basis) ratios of 1:0 (DW alone), 7:3, 1:1, 3:7 and 0:1 (WH alone) to give a total weight of 0.12 kg for each mixture. Each mixture was adjusted to 8% total solids as recommended by Zennaki *et al.* (1996), with portable water. The cow dung was also diluted to 8% total solids and screened using a 6 mm plastic mesh to remove gross solids. Each digester was filled to 60% (15 dm^3) capacity with cow dung slurry (to give sufficient liquid medium for biodegradation and to serve as inoculum to seed the digesters) after which the plant mixtures were loaded. A treatment of cow dung without plant addition was set up to assess the contribution of cow dung to the biogas yield from each treatment. Each treatment was replicated thrice. The daily biogas production was measured by water displacement method. The digesters were manually agitated twice daily at twelve hours interval to ensure intimate contact between the microbes and the substrates, and to release gas bubbles that may have been trapped in the medium. The substrates were digested for 119 days during which ambient and substrates temperatures and biogas yield were measured daily, pH was measured weekly and total bacterial count was measured every four weeks.

Model Concept

First-order kinetic equation can provide an empirical approach to studying the biodegradability of organic materials by observing changes in volatile solids (VS) during decomposition. Hence, the VS biodegradation and maximum biogas yield models used to describe the process and estimate biogas yield, respectively from co-digestion of DW and WH in batch reactors were based on first-order kinetics. It was assumed in this study that: i) there was a correlation between VS degradation and biogas yield at any time; ii) a certain quantity of VS in the substrates was assumed to be recalcitrant to degradation within the retention time allowed (although this was at variance to the assumption by previous researchers (Linke, 2006; Mahnert and Linke, 2009; Yusuf and Ify, 2011). Hence the model was modified to reflect remnant VS; and iii) there was no lag time before the beginning of VS degradation (since biogas production started within 24 h of digestion).

The substrate removal rate is given by:

$$r_C = -\frac{dC_t}{dt} = 0 \quad at \quad 0 \leq t < t_L \qquad (2)$$

$$r_C = \frac{dC_t}{dt} = -k(C_t - C_e) \quad at \quad t_L \leq t \qquad (3)$$

where:

C_t: VS concentration in the substrates at any moment (%, db); $_Lt$: lag time before VS begins to degrade (d); k: VS degradation rate constant based on the quantity of VS in substrate (d^{-1}) and; C_e: remnant VS concentration after retention time (%, db).

By integrating Eq. 3, the VS degradation model is given by:

$$C_t = (C_o - C_e)\, e^{-k(t-t_L)} + C_e \quad at \quad t_L \leq t \qquad (4)$$

Where: Co is VS concentration in the substrates at the beginning of the experiment (%, db).

However, since lag time was assumed to be zero, Eq. 4 becomes:

$$C_t = (C_o - C_e)\, e^{-kt} + C_e \quad at \quad 0 \leq t \qquad (5)$$

Eq. 5 was then log-transformed to linearize it as:

$$ln\left[\frac{(C_t - C_e)}{(C_o - C_e)}\right] = -kt \qquad (6)$$

The original biogas yield data was then transformed using the left side of Eq. 6 to generate a new data set on Y:

$$Y = -kt \qquad (7)$$

Eq. 7 was calibrated with the experimental cumulative biogas yield data of each treatment to obtain the kinetic constant (k).

Maximum biogas yield for each treatment was estimated using the relationship (Yusuf and Ify, 2011):

$$Y_t = Y_m(1 - e^{-kt}) \qquad (8)$$

Where: Y_t and Y_m are biogas yield at any time and maximum biogas yield, respectively.

The half life of first-order kinetic model is given by:

$$t_{1/2} = \frac{ln(2)}{k} = \frac{0.693}{k} \qquad (9)$$

The goodness of fit of the models was evaluated using the R-squared (R^2) statistic and standard deviation (σ). R^2 was calculated from the variance statistics that are reported for the regression, using the equation:

$$R^2 = \frac{SS_{Regression}}{SS_{Total}} \qquad (10)$$

A value of R^2 close to unity indicates a good fit whereas a value close to zero indicates a poor fit. Standard deviation is the average deviation of the residuals (observed minus estimated values for a given data point) from zero. Student's t-test was used to evaluate the observed and estimated data based on the deviation, with the null hypothesis that the overall mean of the residuals did not differ significantly from zero at $p \leq 0.05$. If the resulting p-value of the test is greater than 0.05, it implies that the estimated values closely approximate the observed values.

Statistical Analysis

Experimental data collected was subjected to one-way analysis of variance (ANOVA) using SAS (2002) to compare variations in the parameters measured. Where significance was indicated at $p \leq 0.05$, Duncan's Multiple Range Test was used to separate the means. The curve fitting and goodness of fit analysis was performed using MATLAB 7.8 software (Release 2009a). The experimental biogas yield of each treatment was used to calibrate and validate the model results.

RESULTS AND DISCUSSION

The initial C: N ratios (Table 1) of the individual plant materials were below the optimal range of 16:1-20:1 reported for anaerobic digestion (Alvarez *et al.*, 2010), while that of the cow dung was above. This was due to the high total nitrogen content in the plants compared to the cow dung. However, after mixing the feedstocks, the resulting C: N ratios were higher (35.2:1-36.1:1) than the optimal range. The ash content of the DW (147.8 mg kg^{-1}) was within values (130-150 mg kg^{-1}) obtained in literature (Leng *et al.*, 1995; Noor *et al.*, 2000). The initial moisture content before mixing was 927.9, 898.7 and 572.1 mg kg^{-1} for DW, WH and cow dung, respectively.

Table 1. Initial Properties of the Feedstocks Mixtures

Treatment	Properties (proportion of dry matter)				
	pH[a]	VS (g kg^{-1})	TC (g kg^{-1})	TN (g kg^{-1})	C:N ratio
Individual feedstock					
DW	nd	852.2	473.4	46.2	10.3
WH	nd	981.0	545.0	42.7	12.8
CD	7.50	781.0	433.9	26.1	16.6
Mixture (CD+plants)					
DW:WH (1:0)	6.90	775.1	430.6	26.09	16.5
DW:WH (7:3)	6.97	773.5	429.7	26.13	16.4
DW:WH (1:1)	6.53	773.9	430.0	26.12	16.5
DW:WH (3:7)	6.73	774.4	430.2	26.10	16.5
DW:WH (0:1)	6.60	772.7	429.3	26.15	16.4

[a]1:10 w/v sample: water
VS, volatile solids; TC, total carbon; TN, total nitrogen; C:N, carbon to nitrogen; DW, duck weed; WH, water hyacinth; CD, cow dung; nd, not determined

Table 2. ANOVA Results Showing the Effect of Co-digestion on the Parameters

Parameter	Source	DF	SS	MS	*F*-value	Pr>F
Temperature	Treatment	4	0.3509	0.0877	1.4700	0.2814
	Error	10	0.5953	0.0595		
	Corrected total	14	0.9462			
pH	Treatment	4	0.0939	0.0235	2.4200	0.1172
	Error	10	0.0970	0.0097		
	Corrected total	14	0.0191			
Total bacterial count	Treatment	4	868347047	217086762	7.130	0.0055
	Error	10	304280469	30428047		
	Corrected total	14	1172627516			
Biogas	Treatment	4	0.1145	0.0286	6.628	0.0214
	Error	10	0.0431	0.0043		
	Corrected total	14	0.1598			

DF, degrees of freedom; SS, sum of squares; MS, mean of squares; Pr, probability value

Substrate Temperature

Co-digestion did not have significant ($p > 0.05$) effect on substrate temperature (Table 2). The range of the ambient and substrate temperatures during digestion (25.5 to 33.5 °C and 26.3 to 34.7 °C, respectively) indicated that the anaerobes that caused the decomposition operated within the mesophilic temperature range (25-35 °C). This was considered optimal for the support of biological-reaction rates (Tchobanoglous *et al.*, 2003). The daily substrate temperatures fluctuated repeatedly during digestion.

The temperatures were averaged weekly and presented in figure 1. The temperature profile exhibited sinusoidal pattern; starting with ≈ 26 °C, dropping slightly during week 2 and rising gradually to peak during week 12 in most treatments. There was a sharp increase in temperature values from week 15 to week 16 in all the treatments before decreasing to final values (30.5 to 31 °C). Significant ($p \leq 0.05$) relationship was established between the substrate and ambient temperatures. The high R^2 values (0.878-0.926) obtained between the substrate and the ambient temperatures indicated that heat was exchanged through the digester walls. The relationship was also reflected in the same pattern of ambient and substrate temperatures observed (Figure 1). A significant ($p \leq 0.05$) relationship was also established between the substrate temperatures and the pH. Although the R^2 values (0.295-0.455) were low compared to substrate/ambient temperatures relationship, there was an indication of a dependence of substrate temperature on pH. Substrate temperature varied ($p \leq 0.05$) with total bacterial count in DW: WH (3:7 and 0:1) as indicated by high R^2 values obtained (0.993 and 0.943, respectively).

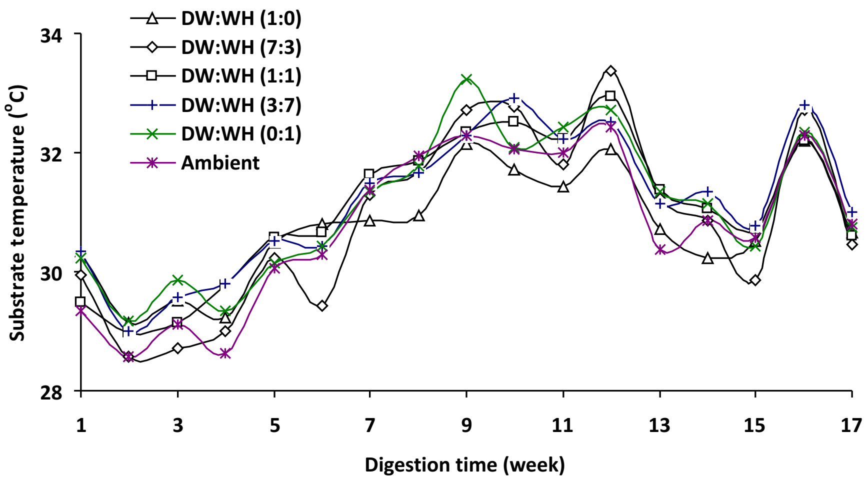


Figure 1. Profile of Substrate Temperature during Digestion
DW, duck weed; WH, water hyacinth

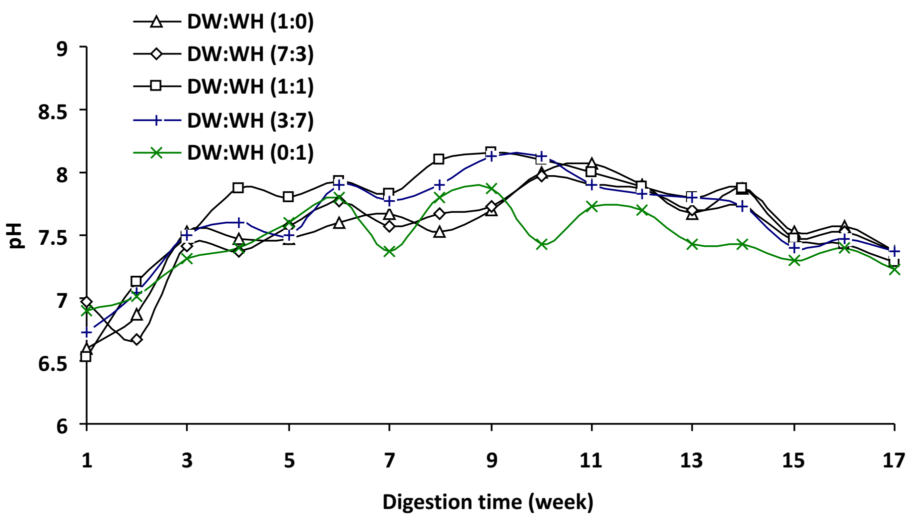


Figure 2. Profile of Substrate pH during Digestion
DW, duck weed; WH, water hyacinth

Substrate pH

Co-digestion had no significant ($p > 0.05$) effect on substrate pH (Table 2). The initial pH of the treatments (Table 1) fell within the range of 6-8 considered suitable for bacteria involved in anaerobic digestion. The pH during digestion ranged between 6.60 and 8.15. pH profile in all the treatments followed the same pattern (Figure 2). Initial values rose gradually to peak (7.40-8.15) between weeks 9 and 11 and dropped gradually thereafter to final values (7.23-7.37). The sinusoidal pattern observed indicated occasional decrease and increase in pH during digestion. The decrease in pH implied the production of volatile fatty acids (Cuzin *et al.*, 1992), while the increase could be attributed to subsequent transfer and consumption of volatile fatty acids by methanogenesis. The sustenance of pH values above 5.0 throughout digestion indicated efficient methane production (Jain and Maattiasson, 1998) and operation of the digesters. The pH final values (>7.20) showed that the effluents were suitable for improvement of agricultural soils (Rynk *et al.*, 1992) and for optimum plant growth (Campbell *et al.*, 1997).

Total Bacterial Count

Co-digestion had significant ($p \leq 0.05$) effect on total bacterial count (Table 2). The mean values showed that DW: WH (7:3 and 0:1) had higher total bacterial count (Table 3). The significant ($p \leq 0.05$) correlation between substrate temperature and total bacterial count in DW: WH (3:7 and 0:1) indicated higher microbial activities which may have resulted in the slightly higher temperatures observed (Table 3). The low and non-significant ($p > 0.05$) R^2 values (0.003-0.346) between pH and total bacterial count implied that the latter did not vary with the former as the pH range during digestion (6.60-8.15) was ideal.

Mosey and Fernandes (1989) reported that the growth of methanogens is greatly reduced below pH 6.6, while Sandberg and Ahring (1992) claimed that an excessive alkaline pH can lead to disintegration of microbial granules and subsequent failure of digestion process. The total bacterial count profile showed steep drops between week 4 and 6 in all the treatments (51225-113600 cfu ml^{-1} to 12100-33950 cfu ml^{-1}) (Figure 3). A slight increase in week 12 was observed in DW: WH (1:0 and 1:1) before decreasing to 7850 and 19025 cfu ml^{-1}, respectively by week 16.

Table 3. Significant Means Separation using the Duncan's Multiple Range Tests

Treatment	Temperature (°C)	pH	Total bacterial count (cfu)	Biogas (dm^3 kg^{-1} VS fed day^{-1})
DW:WH (1:0)	30.56^a	7.57^a	33116^b	0.171^b
DW:WH (7:3)	31.16^a	7.63^a	28131^b	0.176^b
DW:WH (1:1)	31.07^a	7.69^a	29600^b	0.153^a
DW:WH (3:7)	30.86^a	7.54^a	43763^a	0.217^c
DW:WH (0:1)	31.10^a	7.45^a	45919^a	0.238^c

Superscripts with the same letter are not statistically different at $p \leq 0.05$
DW, duck weed; WH, water hyacinth; VS, volatile solids

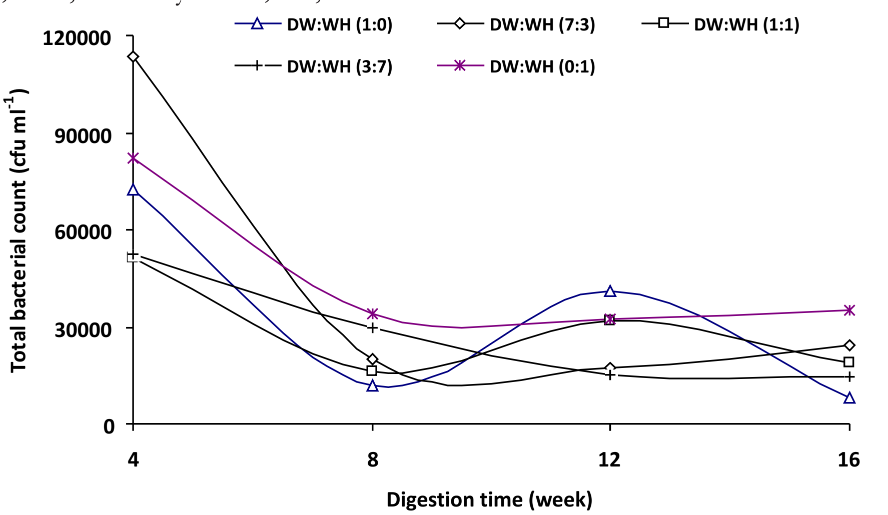


Figure 3. Profile of Total Bacterial Count during Digestion
DW, duck weed; WH, water hyacinth

Biogas Yield

The biogas yield from cow dung treatment was subtracted from the yields of every treatment. Co-digestion was observed to have significant ($p \leq 0.05$) effect on biogas yield (Table 2). DW: WH (1:0) produced the highest while DW: WH (1:1) produced the least. The higher yield in DW: WH (1:0) than DW: WH (0:1) could be attributed to some of the physico-chemical properties (particle size, crude protein, fat, crude fibre and ash) of DW. Duckweed has smaller particle size compared to WH. Furthermore, DW has high crude protein (25-35%) and low fat (1.3%), crude fibre (8-10%) and ash (12-15%) than WH which has crude protein (7.1-8.3%), fat (4.4%) crude fibre (16.9-21.9%), ash (19.1-24.7%) (Okoye *et al.*, 2002; Hlophe and Moyo, 2011; Zhao *et al.*, 2014).

The effect of particle size on biogas production has shown that finer particles resulted in greater biogas production (Moorhead and Nordstedt, 1993; Mshandete *et al.*, 2006; Nalinga and Legonda, 2016). High protein content has been reported to favour biogas production (Eze and Ojike, 2012) as crude protein degrades to cellulotic materials during fermentation to yield biogas by micro-organisms secreting some extra cellular enzymes (proteins). Fibre materials are not susceptible to easy degradation due to the high percentage of lignin content which makes it resistant to attack by anaerobic micro-organisms, hence they result in low biogas yield. The significantly higher yield could also be attributed to a greater synergy between cow dung and DW in the resulting low C: N ratio mixture. Biogas yield had non-significantly ($p > 0.05$) low R^2 values when it was correlated with substrate temperature (0.004-0.067), total bacterial count (0.004-0.816) and pH (0.003-0.187) in all the treatments. Regardless of the high initial C: N ratios of the treatments, biogas production started within 24 h of digestion (Figure 4a). The early production could be due to the high VS content in the starting mixtures (Table 1) or possibly a synergetic effect due to the complementary characteristics of the feedstock materials mixed (Comino *et al.*, 2010) or the high water content in the aquatic weeds. Also, all the treatments had varying days of non-production. The zero productions showed that none of cow dung and plant(s) produced biogas. This can be attributed to methanogens undergoing a methamorphic growth process by consuming methane precursors produced from the initial activity (Lalitha *et al.*, 1994) or temporary inhibition of the digestion process due to volatile fatty acid accumulation (Bouallagui *et al.*, 2001). The total non-production days were 11, 23, 35, 26 and 35, amounting to 9.24, 19.32, 29.41, 21.85 and 29.41% of digestion time in DW: WH (1:0, 7:3, 1:1, 3:7 and 0:1), respectively. The longest consistent non-production days (11 days) were observed in DW: WH (0:1) from day 109 to the end of the experiment which, signaled the completion of the digestion process. DW: WH (1:1) had 8 days, DW: WH (7:3 and 3:7) had 7 days each while DW: WH (1:0) had the least (3 days). The weekly yield showed repeated fluctuations during digestion (Figure 4b). DW: WH (1:0, 7:3, 1:1 and 3:7) attained peak productions during week 5, of which 42.7, 40.5, 42.9 and 38.1%, respectively of the total biogas yield had been produced. DW: WH (0:1) attained its peak production during week 8, of which 62.4% of the total biogas yield had been produced. The differences in peak periods were attributed to the differences in the degree of biodigestibility of the plants (Odeyemi and Adewumi, 1982). It was observed from the cumulative yields (Figure 4c) that from day 18, DW: WH (1:0) had consistently higher yield followed by DW: WH (7:3) from day 24. DW: WH (3:7) maintained the least yield from day 67 thereafter.

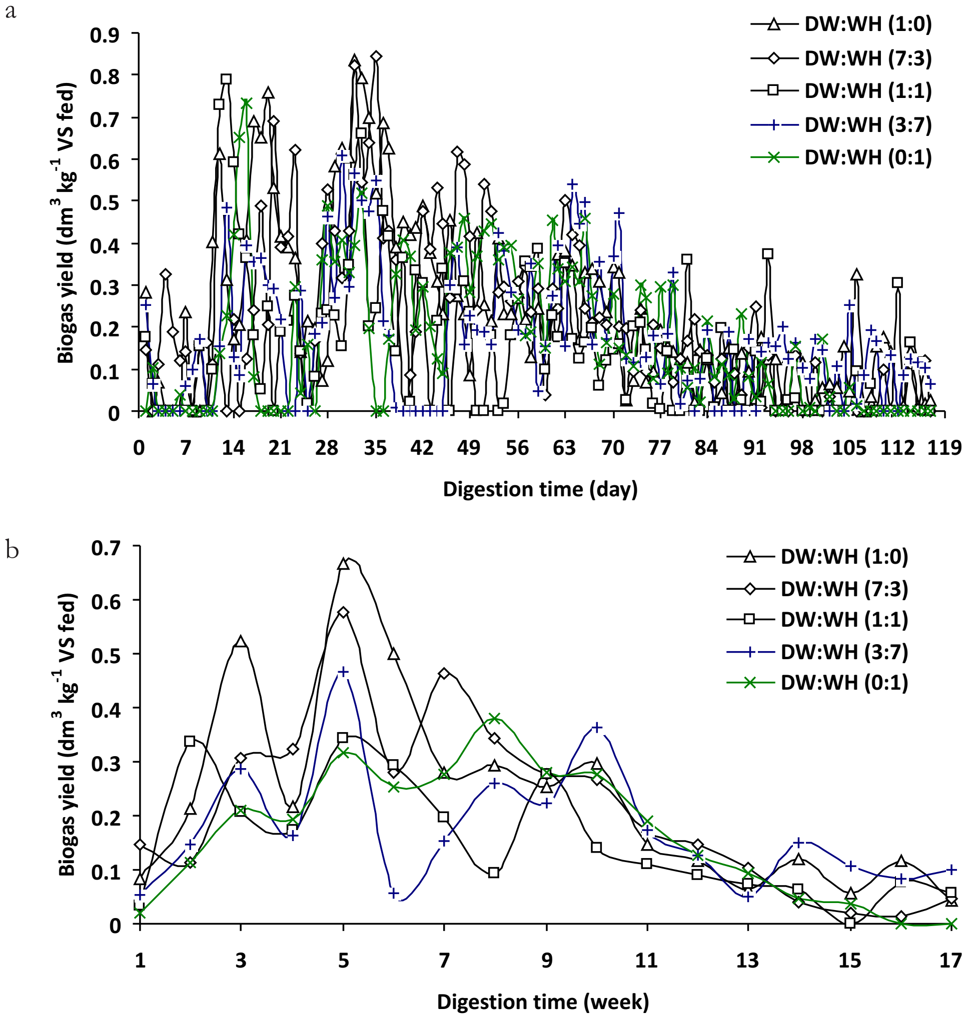
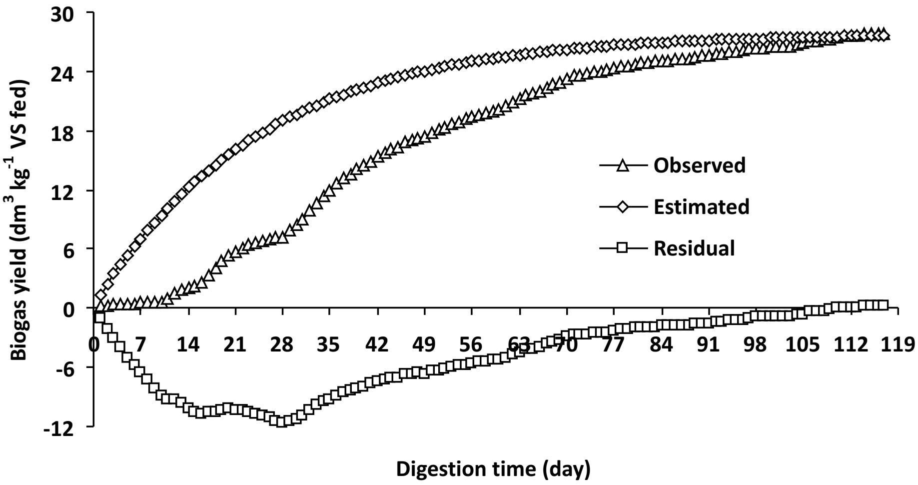


Figure 4. Profile of Biogas Yield (a) Daily and (b) Weekly
DW, duck weed; WH, water hyacinth: VS, volatile solids

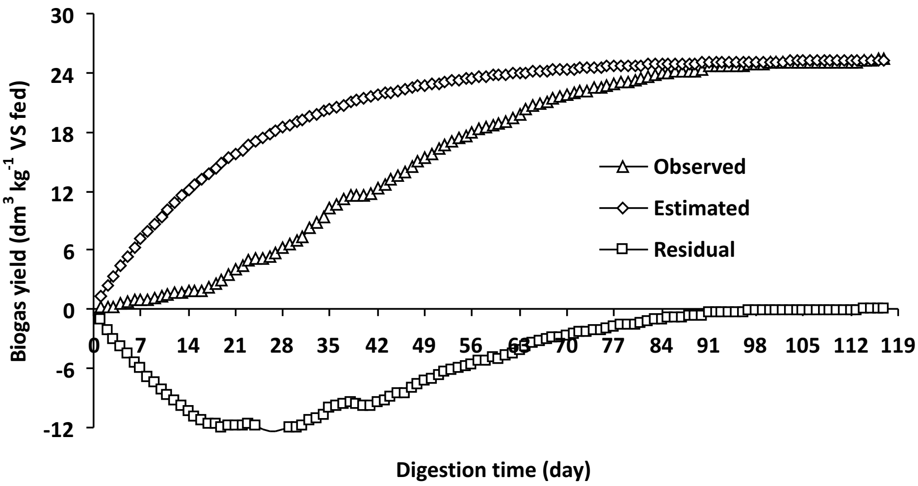
Modelling Results

The summary of modeling results on the yields from the water weeds are presented in table 4. The biodegradation model (Eq. 5): The rate constants (*k*) for the treatments varied between 0.0326 and 0.0481 d^{-1}, with DW: WH (1:1) having the least. The *k* values were similar to what Adanikin *et al.* (2017) obtained. The lower the *k*, the lower the biodegradation rate. No significant correlation was established between *k* and biogas yield. The same was observed by Mahnert and Linke (2009). The goodness of fit test showed high R^2 values (>0.7369) for the treatments, indicating that the biogas yield obtained can be explained satisfactorily by the biodegradation model. The estimated yields followed a first-order kinetic reaction (Figure 5a-e). However, the *t*-test analysis showed that the estimated yield did not closely approximate the observed yields in all the treatments. This was largely attributed to the high residual values in the early days of digestion (Figure 5a-e). However, towards the end of digestion, the estimated values tend towards the observed values, resulting in residual values closer to zero. Particularly, DW: WH (1:1 and 3:7) had no significant ($p > 0.05$) difference between the observed and estimated yields from day 100 to the end of digestion. Other treatments observed the same from about day 110 to the end of digestion. The observation suggests that the biodegradation model may not be suitable for short retention time. Both residual mean and residual standard deviation was least and highest in DW: WH (1:1) and DW: WH (7:3), respectively. The time at which half of the yield was produced, t_{21}, which was a function of *k*, varied linearly with *k*, with DW:WH (1:1) having the longest half time. The maximum biogas yield (*Ym*) model (Eq. 8): The *R2* values (>0.583) (Table 4) obtained from the regression analysis showed that the model can satisfactorily be used to estimate *Ym* from anaerobic digestion. This fact was further proven by the high values of estimated *Ym*/observed *Ym* (75-85%) and the high correlation (*R* = 0.979) between the two yields. The estimated maximum yields showed that DW: WH (1:0) had higher yield than DW: WH (0:1) (Table 4), the same trend as obtained in the original yield (Table 3). The estimated yields also showed that co-digestion improved biogas yield from WH, with DW: WH (7:3) having the highest *Ym*. With the high correlation reported between the observed and estimated yields, it could be said that a significant ($p \leq 0.05$) difference would also exist among the estimated yields. The modeling results showed that for both biodegradation and maximum biogas yield models, DW: WH (1:1) and DW: WH (0:1) had the best and least model fit, respectively as indicated by their corresponding R^2 values.

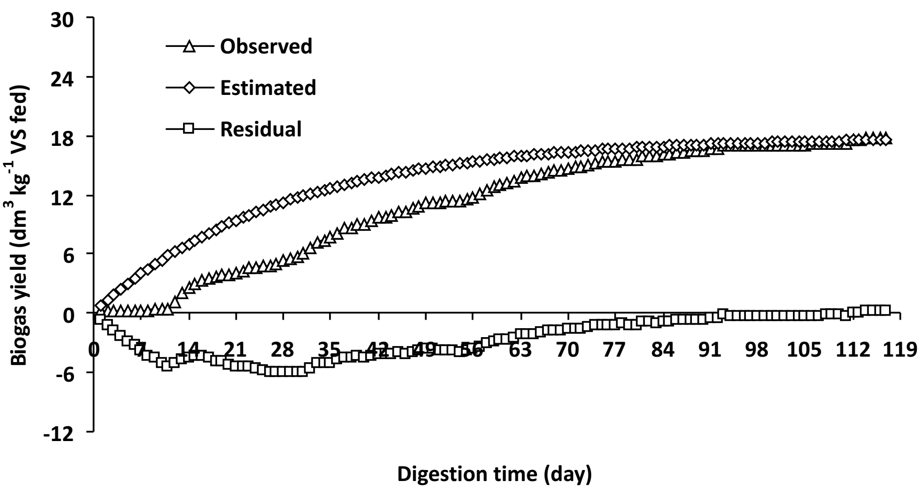
a



b



c



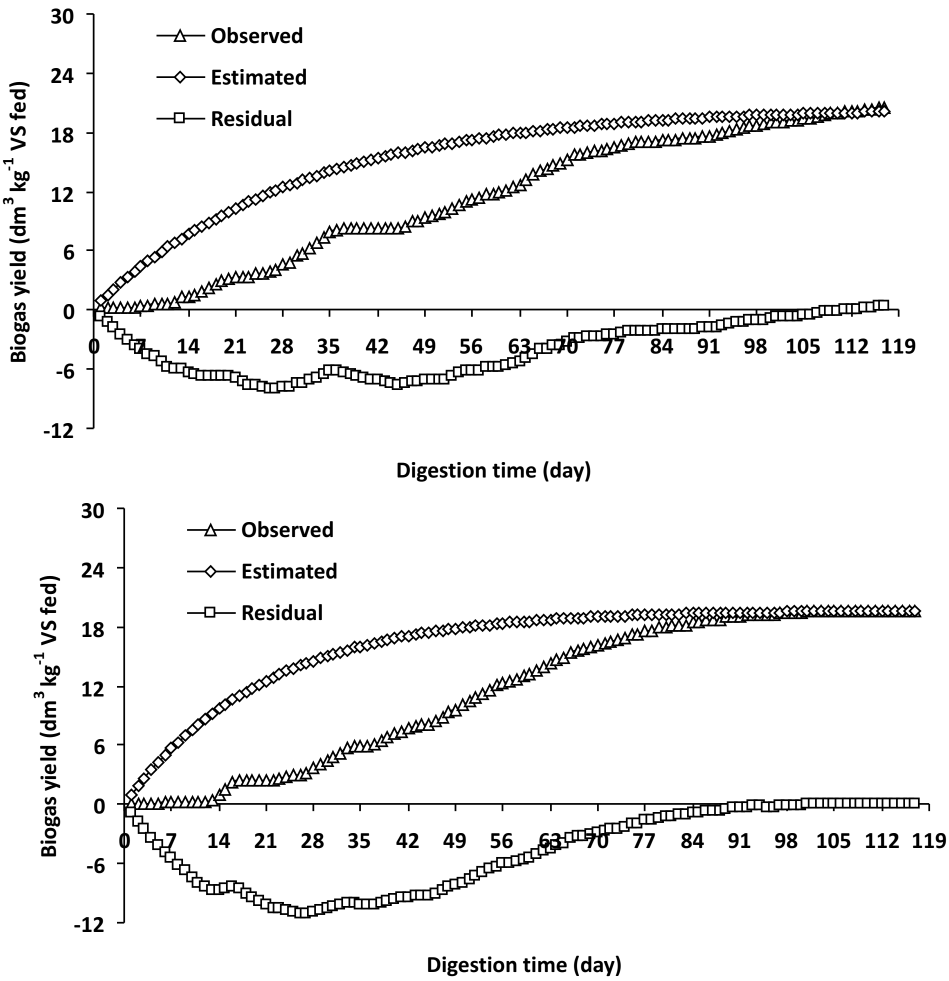


Figure 5. Profile of Observed and Estimated Cumulative Biogas Yield:
a) DW:WH (1:0), b) DW:WH (7:3), c) DW:WH (1:1), d) DW:WH (3:7) and e) DW:WH (0:1)
Residual = Observed Estimated.
DW, duck weed; WH, water hyacinth; VS, volatile solids

Table 4. Summary of Modeling Results

Treatment	Biodegradation model						Maximum biogas yield (Y_m) model		
	k (d^{-1})	R^2	R_μ	R_σ	t-test	$t_{1/2}(d)$	Estimated Y_m (dm^3 kg^{-1}VS fed)	R^2	Estimated/Observed (%)
DW:WH (1:0)	0.0481	0.7369	-4.759	4.048	<0.001	14.40	14.86 (19.68)	0.5838	75.51
DW:WH (7:3)	0.0326	0.8671	-4.088	2.711	<0.001	21.26	16.15 (20.55)	0.7487	78.59
DW:WH (1:1)	0.0351	0.9219	-2.601	2.005	<0.001	19.75	15.26 (17.86)	0.8192	85.47
DW:WH (3:7)	0.0460	0.8149	-5.041	4.386	<0.001	15.08	20.40 (25.39)	0.6730	80.35
DW:WH (0:1)	0.0404	0.8878	-4.950	3.752	<0.001	17.13	22.93 (27.85)	0.7598	82.34

Values in parenthesis are the real Y_m; k, volatile solids degradation rate constant; R_μ, residual mean; R, residual standard deviation
DW, duck weed; WH, water hyacinth; VS, volatile solids

CONCLUSIONS

The results showed that co-digestion had significant effect on total bacterial count and biogas yield. Duckweed produced more biogas than water hyacinth while DW: WH (7:3) produced the highest among the plant mixtures. The high R^2 values obtained from the models fit showed that biodegradation model fitted and described the experimental biogas yields satisfactorily while the maximum biogas yield model also predicted the maximum yields satisfactorily. Biogas yield from DW: WH (1:1) was the best described by the two models, as indicated by the highest R^2 values.

REFERENCES

Adanikin, B.A., Ogunwande, G.A. and Adesanwo, O.O. 2017. Evaluation and kinetics of biogas yield from morning glory (*Ipomea asarifolia*) co-digested with water hyacinth (*Eichhornia crassipes*). *Ecological Engineering,* 98: 98-104.

Almoustapha, O., Kenfack, S. and Millogo-Rasolodimby, J. 2009. Biogas production using water hyacinths to meet collective energy needs in a Sahelian country. *Field Action Science Report*, 73-77.

Alvarez, J.A., Otero, l. and Lema, J.M. 2010. A methodology for optimizing feed composition for anaerobic co-digestion of agro-industrial wastes. *Bioresource Technology,* 101: 1153-1158.

Bouallagui, H., Ben Cheikh, R., Marouani, L. and Hamdi, M. 2001. Fermentation methanique des dechets solides en batch. Les premieres journees de l'Association Tunisienne de Biotecnologie. Sousse le 9-10 et 11 Fevrier.

Bremner, J.M. 1996. Nitrogen-total. In: Sparks DL (ed.), *Methods of Soil Analysis. Part 3-Chemical Methods*. Madison, WI, USA: SSSA Inc., ASA Inc, pp.1085–122.

Campbell, A.G., Folk, R.L. and Tripepi, R. 1997. Wood ash as an amendment in municipal sludge and yard waste composting processes. *Compost Science and Utilization,* 5: 62-73.

Clark, P.B., Hillman, P.F. and Eng, C. 2007. Enhancement of Anaerobic digestion using duckweed (*Lemna minor*) enriched with iron. *Water and Environment Journal,* 10 (2): 92-95.

Comino, E., Rosso, M and Riggio, V. 2010. Investigation of increasing organic loading rate in the co-digestion of energy crops and cow manure mix. *Bioresource Technology* 101: 3013-3019.

Cuzin, N., Farinet, J.L., Segretain, C. and Labat, M. 1992. Methanogenic fermentation of cassava peel using a pilot plug flow digester. *Bioresource Technology,* 41: 259-264.

Eze, J.I. and Ojike, O. 2012. Anaerobic production of biogas from maize wastes. *International Journal of the Physical Sciences,* 7(6): 982 – 987.

Gaur, R.Z., Khan, A.A. and Suthar, S. 2017. Effect of thermal pre-treatment on co-digestion of duckweed (*Lemna gibba*) and waste activated sludge on biogas production. Chemosphere*,* 174: 754–763.

Hlophe, S.N. and Moyo, N.A.G. 2011. The effect of different plant diets on the growth performance, gastric evacuation rate and carcass composition of *Tilapia rendalli.* Asian *Journal of Animal and Veterinary Advances,* 6: 1001- 1009.

Hunter-Cerena, J.C., Fonda, M. and Belt, A. 1986. Isolation of Cultures. In: Demain AL and Solomon NA (eds.) *Manual of Industrial Microbiology and Biotechnology*. ASM Publication, pp.3-23.

Jain, S.R. and Maattiasson, B. 1998. Acclimatization of methanogenic consortia for low pH biomethanation process. *Biotech Letter,* 20 (8): 771-772.

Kusina, J., Mutisi, C., Govere, W., Mhona, R., Murenga, K., Ndamba, J. and Taylor, P. 1999. Evaluation of duckweed (Lemna minor) as a feed ingredient in the finisher diets of broiler chickens. *Journal of Applied Science in Southern Africa,* 5 (1): 25-34.

Lalitha, K., Swaminathan, K.R. and Bai, R.P. 1994. Kinetics of biomethanation of solid tannery waste and the concept of interactive metabolic control. *Applied Biochemistry and Biotechnology,* 47: 73-87.

Leng, L.A., Stambolie, J.H. and Bell, R. 1995. Duckweed - a potential high-protein feed resource for domestic animals and fish. Livestock Research for Rural Development 7 (5). Retrieved October 31, 2016, from http://www.lrrd.org/lrrd7/1/3.htm

Linke, B. 2006. Kinetic study of thermophilic anaerobic digestion of solid wastes from potato processing. *Biomass and Bioenergy,* 30 (10): 892-896.

Mahnert, P. and Linke, B. 2009. Kinetic study of biogas production from energy crops and animal waste slurry: Effect of organic loading rate and reactor size. *Environmental Technology,* 30 (1): 93-99.

MATLAB 7.8 2009. *MATLAB & Simulink Release 2009a.* The MathWorks Inc., 3 Apple Hill Drive, Natick, MA 01760-2098.

Mercer, W.A. and Rose, W.W. 1968. *Investigation of Windrow Composting as a Means for Disposal of Fruit Waste Solid.* Washington, DC. National Canners Association Research Foundation.

Moorhead, K.K. and Nordstedt, R.A. 1993. Batch anaerobic digestion of water hyacinth: Effects of particle size, plant nitrogen content, and inoculums volume. *Bioresource Technology,* 44: 71-76.

Mosey, F.E. and Fernandes, X.A. 1989. Patterns of hydrogen in biogas from the anaerobic-digestion of milk-sugars. *Water Science and Technology,* 21: 187-196

Mshandete, A., Bjomsson, L., Kivaisi, A.K., Rubindamayugi, M.S.T. and Mattiasson, B. 2006. Effect of particle size on biogas yield from sisal fibre waste. *Renewable Energy* 31 (14): 2385-2392.

Nalinga, Y. and Legonda I. 2016. The effect of particles size on biogas production the effect of particles size on biogas production. *International Journal of Innovative Research in Technology and Science,* 4 (2): 9-13.

Narayana, J. and Parveez, S. 2000. Treatment of paper mill effluent using water hyacinth (*Eichhornia crassipes*). *Journal of Industrial Pollution Control,* 16 (2): 161-164.

Noor, J., Hossain, M.A., Bari, M.M. and Azimuddin, K.M. 2000. Effects of duckweed (*Lemna minor*) as dietary fishmeal substitute for silver barb (Bar bodes gonionotus Bleeker). *Bangladesh Journal of Fisheries,* 4 (1): 35-42.

Odeyemi, O. and Adewumi, A.A. 1982. Relative Biogas Generation from Animal Manures in Nigeria. In: Energex '82: A forum on energy self-reliance: conservation, production and consumption (Curtis, F.A. (Ed.). Conference proceedings, Solar Energy Society of Canada, Regina, Saskatchewan, Canada, pp. 285-287.

Okoye, P.C., Daddy, F. and Ilesanmi, B.D. 2002. The nutritive value of water hyacinth (*Eichhornia crassipes*) and its utilisation in fish feed. Proceedings of the International Conference on Water Hyacinth. National Institute for Freshwater Fisheries Research, Nigeria, pp. 65-70

Patil, J.H., Raj, M.A., Muralidhara, P.L., Desai, S.M. and Raju, G.K.M. 2012. Kinetics of anaerobic digestion of water hyacinth using poultry litter as inoculum. *International Journal of Environmental Science and Development,* 3 (2): 94-98.

Polprasert, C., Kongsricharoern, N. and Kanjanaprapin, W. 1994. Production of feed and fertilizer from water hyacinth plants in the tropics. *Waste Management and Research*, 12 (1): 3-11.

Rynk, R., van de Kamp, M., Wilson, G.B., Singley, M.E., Richard, T.L., Kolega, J.J., Gouin, F.R., Laliberty, L., Kay Jr, D., Murphy, D.W., Hoitink, H.A.J. and Brinton, W.F. 1992. On-farm composting. Ithaca, NY, USA: Northeast Regional Agricultural Engineering Services.

Sandberg, M. and Ahring, B.K. 1992. Anaerobic treatment of fish-meal process waste-water in a UASB reactor at high pH. *Applied Microbiology and Biotechnology,* 36: 800-804.

SAS, 2002. *Statistical Analysis Software Guide for Personal Computers.* Cary, NC 27513, USA: Release 9.1 SAS Institute Inc.

Singhal, V. and Rai, J.P.N. 2003. Biogas production from water hyacinth and channel grass used for phytoremediation of industrial effluents. *Bioresource Technology,* 86: 221-225.

Strom, E. 2010. Leachate treatment and anaerobic digestion using aquatic plants and algae. MSc Thesis, Linkoping University, Sweden.

Sullivan, C.O., Rounsefell, B., Grinham, A., Clarke, W. and Udy, J. 2010. Anaerobic digestion of harvested aquatic weeds: water hyacinth (*Eichhornia crassipes*), cabomba (*Cabomba Caroliniana*) and salvinia (*Salvinia molesta*). *Ecological Engineering,* 36: 1459-1468.

Tchobanoglous, G., Burton, F.L. and Stensel, H.D. (2003) Waste-water engineering: treatment and reuse. Fourth edition, New Delhi: Tata McGraw-Hill Publishing Company Limited, p.1819.

Tonon, G., Magnus, B.S., Mohedani, R.A., Leite, W.R.M., da Costa, R.H.R. and Filho, P.B. 2017. Pre-treatment of duckweed biomass, obtained from wastewater treatment ponds, for biogas production. *Waste and Biomass Valorization* 8: 1–7.

Triscari, P.A., Henderson, S.L. and Reinhold, D.M. 2009. Anaerobic digestion of dairy manure combined with duckweed (Lemnaceae). *ASABE Annual International Meeting,* 2: 980-989.

Yusuf, M.O.L. and Ify, N.L. 2011. The effect of waste paper on the kinetics of biogas yield from the co-digestion of cow dung and water hyacinth. *Biomass and Bioenergy,* 35: 1345-1351.

Zennaki, B.Z., Zadi, A., Lamini, H., Aubinear, M. and Boulif, M. 1996. Methane fermentation of cattle manure: effects of HRT, temperature & substrate concentration. *Tropicultural,* 14 (4): 134-140.

Zhao, Y., Fang, Y., Jin, Y., Huang, J., Bao, S., Fu, T., He, Z., Wang, F. and Zhao, H. 2014. Potential of duckweed in the conversion of wastewater nutrients to valuable biomass: a pilot-scale comparison with water hyacinth. *Bioresource Technology,* 163: 82-91.