Chapter

Biogas Generation from Co-Digestion Waste Systems: The Role of Water Hyacinth

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Abstract

Using biomass as a renewable energy source has earned tremendous interest from researchers in recent decades, especially because the technology is environmentally benign. This article reviews the recent methods for generating biogas from water hyacinth (WH, *Eichornia crassipes*), arguably the world's most evasive aquatic macrophyte. Therefore, various economic, environmentally benign, and renewable procedures that enhance biogas production from WH biomass are reviewed. WH has been co-digested with numerous waste types, including poultry droppings, municipal wastes, animal tissue wastes, pig wastes, cow dungs, etc., recording varying success degrees. Other studies focused on optimizing the operation parameters, such as mixing ratio, contact time, pH, temperature, organic loading rate, etc. We observed that most attempts to generate biogas from WH alone were not promising. However, when co-digested with other biomasses or wastes, WH either increases the process rate or improves the methane yield content. Also, the potential of WH as a phytoremdiator-cum-biogas source was investigated. This chapter provides mathematical models, scale-up installation models, and specific experimental results from various studies to guide future study plans toward optimizing CH_4 generation from WH co-digestion.

Keywords: *Eichornia crassipes*, biomethanation, methanogens, biogas yield, biogas purity

1. Introduction

Biogas, an energy source comprising CH_4, CO_2, and traces of some gaseous impurities, is generated via biomethanation, i.e., anaerobic digestion of substrates. Irrespective of the substrate, typical biogas is composed of 50–80% CH_4, 20–50% CO_2, 5–10% of H_2, 1–2% of N_2, ≈0.3% water vapor, and traces of H_2S and $H_2O_{(g)}$ [1, 2]. Regardless of their proportions, CO_2 and H_2S are the major impurities in biogas. Therefore, post-production cleanup processes are required to remove them for optimum performance of the final product. Usually, CO_2 is absorbed into hydroxides of

Ca, K, or Ba (Eq. (1)), while $CuSO_4$ removes H_2S, $FeSO_4$, $Pb(NO_3)_2$, or $FeCl_3$ (Eq. (2)). For CO_2 removal, NaOH is an efficient absorbent, although KOH is 27% more effective, using only 125 kWh/Tor CO_2 energy [3]. Otherwise, to minimize the cost and avoid additional waste generation, the pristine gas stream could be bubbled through water to remove both gases, albeit with less efficiency [4].

$$Ca(OH)_{2(aq)} + CO_{2(g)} \longrightarrow CaCO_3 + H_2O \tag{1}$$

$$(CH_3COO)_2Pb_{(aq)} + H_2S_{(g)} \longrightarrow 2CH_3COOH_{(aq)} + PbS_{(s)} \tag{2}$$

2. Biodigestion process

A typical biodigester is made of concrete, metal, or other material that permits anaerobic biomass fermentation [5]. For optimum performance, the operational and ambient conditions must be diligently considered. Several factors that affect biogas production efficiencies include pH, temperature, type and quality of the substrate, mixing speed and consistency organic loading, formation of highly volatile fatty acids, and inadequate alkalinity [6]. The retention (turn-over) time is the period required for organic materials to be decomposed entirely toward achieving maximum biogas yield. Fertilizers and mineralized water are the usual valuable by-products of this process [5].

Research into biogas technology in Africa gained momentum in the last decade. For instance, in Nigeria, biogas production from Bambara nut chaff [6], agricultural waste [7], and abattoir waste [8], and the performance evaluation of a biogas stove for cooking [9] have been reported. Furthermore, biogas generation from co-digested substrates, such as spent grains and rice husk [10], banana and plantain peels [11], pig waste and cassava peels [12], sewage and brewery sludge [13], have also been experimented. In most cases, co-digestion enhances methane yield by ≈60%. Similar studies were carried out in other African countries such as Uganda [14], South Africa [15], Sudan [16], etc.

Generally, plant-based biofuels are environmentally clean energy, with a high potential of lowering fossil fuel consumption to the barest minimum in the near future [17]. Over the past decade, several studies have focused on producing biomethane using lignocellulosic residues of high abundance and low cost [18, 19]. According to Bekkering et al. [20] and Holm-Nielsen et al. [21], biogas can be used as fuel and fuel cells to generate heat, steam, electricity, produce chemicals, upgrade natural gas grids via injection, etc. Elsewhere, Jantsch and Mattiasson [22] discussed how anaerobic digestion could treat wastewater and organic wastes, yielding biogas as a valuable by-product. The four major sources of biogas production are livestock waste, landfill gas (LFG), activated sludge from wastewater treatment plants, and IIC (industrial, institutional, and commercial waste) [22–24].

Biomethanation occurs in four main steps (**Figure 1**) viz. hydrolysis [23] , acidogenesis [24], acetogenesis [26], and methanogenesis [27]. Methane is the main component of biogas (50–70%). Other components include CO_2 (30–40%) and traces of H_2S and $H_2O_{(g)}$ [28]. The respective equations for the four steps are provided as Eqs. (3)–(6):

$$\text{Hydrolysis}: (CsH_{10}O_5) + nH_2O \longrightarrow n(C_6H_{12}O_6) \tag{3}$$

$$\text{Acidogenesis}: n(C_6H_{12}O_6) \longrightarrow 3nCH_3COOH \tag{4}$$

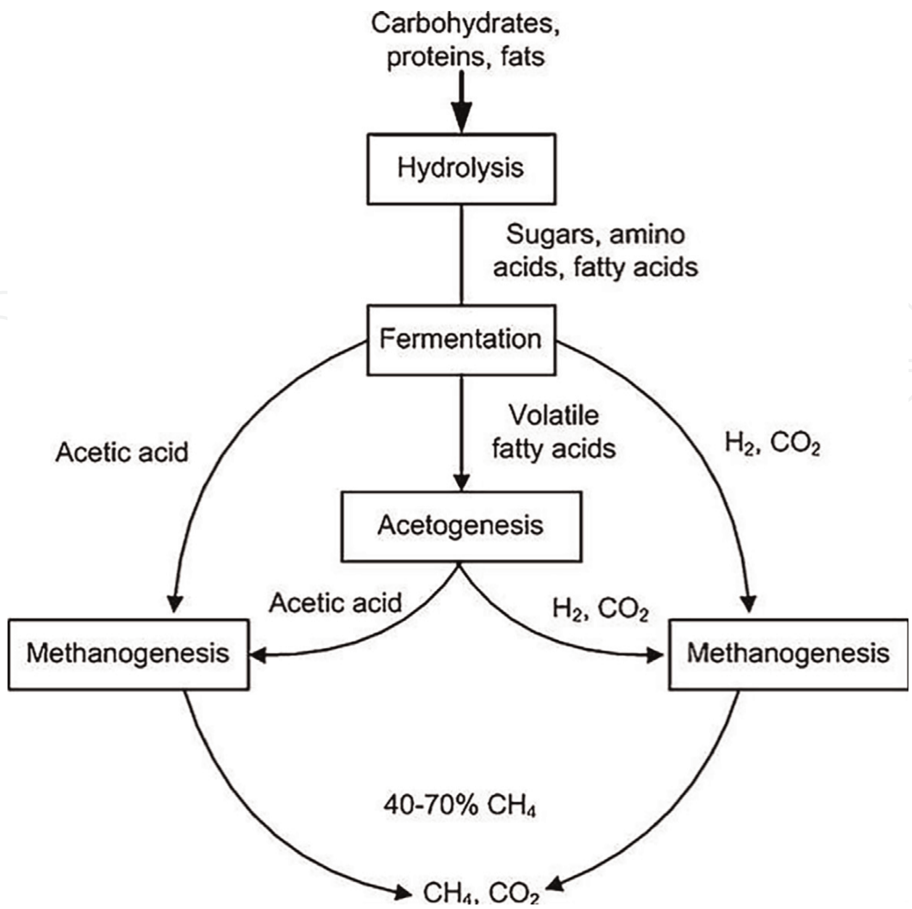

Figure 1.
Process flow of the degradation of organic material through anaerobic digestion [24, 25].

$$\text{Acetogenesis}: CH_3COOH \longrightarrow CH_4 + CO_2 \tag{5}$$

$$\text{Methanogenesis}: CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \tag{6}$$

Four major microbial groups are respectively involved: the hydrolytic-fermentative bacteria (hydrolyze complex organic compounds into simple ones), fermentative bacteria (convert the simple organic compounds into volatile fatty acids, yielding H_2 and CO_2), acetogenic bacteria (convert the fatty acids into acetic acid), and methanogenic archaea (produce CH_4 either from acetate or from H_2 and CO_2) [24, 25].

3. Factors affecting biogas yield and production

The quality of manure influences the methanogenic diversity in a reactor, and the overall conversion efficiency of manure to CH_4 is influenced by the retention time [29], pH, oxygen level, NH_3-N, and volatile fatty acids (VFA) contents, and temperature [30, 31]. Biogas can be produced under psychrophilic (10–30°C), mesophilic (20–50°C), and thermophilic (50–75°C) conditions [2]. Mesophilic and thermophilic conditions present different reactor designs, operational advantages, and drawbacks. Most anaerobic digesters are designed to operate at mesophilic (40°C) or thermophilic (55°C) temperature to maximize biogas yield [32], whereas, between 40 and 50°C, methanogens are inhibited. Elsewhere, anaerobic digestion temperature was optimized at 25–38°C (mesophilic conditions), with temperatures near 38°C showing more excellent (≥95%) digestion stability. Likewise, a mesophilic treatment at 38°C reportedly destroys 99.9% of pathogens [33].

Similarly, the C/N [34, 35], slurry concentration, mixing rate, and bacteria type (starter) are other crucial parameters that influence biogas quality and yield [36]. Typically, the organic loading rate (OLR) ranges between 0.5 and 3 kg VS (volatile solids) per m^3 per day [29]. **Table 1** lists the average C/N of various substrates used for biogas production [70–72]. Typical C/N values/ranges for biogas production are as follows: liquid cattle manure (6–20), chicken manure (3–10), liquid swine manure (5), straw (50–150), grass (12–26), potatoes (35–60), sugar beet/beet foliage (35–46), cereals (16–40), fruits and vegetables (7–35), mixed food waste (15–32), slaughterhouse waste—soft tissue (4), slaughterhouse waste—guts (22–37), food waste (3–17), distillery waste (8), etc. An increasing C/N (10–30) increases the formation of fatty acids in the process [34, 35]. If the fatty acid concentrations are not sufficiently high, methanogenesis could result.

Methanogens are sensitive to rapid temperature change, while thermophilic methanogens are more temperature-sensitive counterparts. Therefore, temperature should be kept exactly at ±2°C [2].

Some researchers have investigated the optimal pH for microbial performance during anaerobic digestion. According to Yadvika et al. [73], the pH within the digester should be kept within 6.8–8.0, whereas Thy et al. [74] concluded that 6–8 pH range is the optimal pH. At the onset of the acid-forming stage of the digestion, the pH may be <6.0. However, it could be >7.0 during methane formation and maintained because it is sensitive to acidity. In a properly operating anaerobic digester, a pH of 6.8–7.2 converts volatile acids to CH_4 and CO_2 [75]. The pH is the most suitable indicator for plausible digester instability after gas production [29]. Initially, the pH would decrease as the organic matter undergoes acetogenesis. However, as the methanogens rapidly consume the acids, the pH rises, stabilizing the digester performance. Fermentative bacteria require a pH > 5.0 to become enzymatic, while methanogenic activity takes place at a pH range of 6.2–8.0, optimized at ±7.1 [29, 76]. In addition, other phenomena, such as the dissociation of important compounds (ammonia, sulfide, organic acids, etc.), are directly affected by pH [32]. Methanogenic bacteria are generally susceptible to pH and do not thrive at pH < 6.0 [77].

Homogeneous mixing within the digester improves the contact between the microorganisms substrate, improving the bacterial ability to obtain required nutrients. Also, by homogenization, scum formation and temperature increase within the digester are minimized. However, excessive mixing can disrupt the microorganisms; therefore, slow mixing is preferred [78]. According to Kossman et al. [79], with other parameters fixed, a well-agitated substrate can increase biogas production by 50%.

4. Various biomasses for biogas production

The anaerobic fermentation of manure for biogas production does not compromise the quality of the fertilizer supplement because the nitrogen and other substances remain in the treated sludge [80]. In the absence of appropriate disposal methods, animal dungs can cause various environmental and health problems, such as pathogenic contamination, odor pollution, and greenhouse gas emission [81]. Rain may flush these wastes into neighboring water bodies or percolate underground, springs,

S/N	Starting material	CH_4 yield	Substrate mixing ratio/ concentration	Biogas yield	Observation	Experimental condition	Ref.
WH only							
1	WH only	72.53%	5–30 g/L		Shoots only generated 6.86% extra methane	39°C substrate; concentration 25 g/L	[37]
2	WH only		C/N 35	202 L/ kg TS	TS not a significant factor	TS 1.59% ; 60 days	[38]
3	WH only	50–65%	C/N 16		No link between C/N ratio and production	51 days	[39]
4	WH only		1:4 (WH: Wate) C/N: 15	245 L/ kg VS		60 days; 30–37°C	[40]
5	WH only	65%		380 L/ kg VS	Pretreatment with NaOH yielded most methane composition (71%)	35°C; size 2 cm; 60 days	[41]
6	WH only		C/N: 25.9	75 L/kg TS		pH: 6.65; TS: 8%; size = 2 cm	[42]
7	WH only			360.1 L/ kg TS		40 days; Size: 1 cm; 45°C	[43]
8	WH only			221 L/kg TS	Increase of 75.61%	Size = 1 cm; pretreated at 60°C for 24 h	[44]
Co-digested WH							
9	WH + cow dung		C/N : 32.0	108 L/ kg TS	Microbial consortium 7.26%	60 days; size = 15 cm; TS 5–10%	[45]
10	WH + MW[1]			16 L/kg		36-37°C ; pH 6.0–7.4	[46]
11	WH + MW	60.5%	4:1 (WH: waste)	230 L/ kg VS		TS = 4%; 15 days	[47]
12	WH + other biomass	68.67%		237.4 L; CH_4/kg VS		F:M = 1:1; 60 days	[48]
13	WH + other biomass		Duckweed: WH = 7:3; C/N = 16.4	20.55 L/ kg VS		8% TS size < 6 mm	[49]
14	WH + other biomass		Salivinia: WH = 0.5:1	406 L/ kgVS	VFA affected WH in 3:1		[50]
15	WH + other animal wastes	52.8%	1:2 (WH: Buffalo dung)	2.86 L/ day	Pretreatment increased biogas production by 102%; methane by 51%	Size: 6 mm	[51]

S/N	Starting material	CH_4 yield	Substrate mixing ratio/ concentration	Biogas yield	Observation	Experimental condition	Ref.
16	WH + poultry droppings		2:8 9 (WH: poultry manure)	34.65 L/kg		40 days	[52]
17	WH + cow dung	49–53% upgraded to 73%	3:1 (WH: cow dung)	3.2 L/kg		22.8–36.6°C	[53]
18	WH + cow dung	63.7%			Optimal OLR un-pretreated		[54]
19	WH + MW		F/M = 10.01 : 0.03	152 L/kg TS (daily)	TS = 6.76%		[55]
20	WH + cow dung	65%		270 L/m^3	22%	Size = 5 cm; 10 days	[56]
21	WH + cow dung	56.4%	2:1 (WH: cow dung) C/N 10:1	3050 L/ day		40 days; size = 2–5 cm; 28–36.7°C; pH = 6.5–7.8	[57]
22	WH + pig waste	88.3%	1:3 (WH: Pig waste)			27–34°C	[58]
23	WH + pig waste	1.4 kg : 1L (piggery waste:WH) C/N = 30:1				TS = 14.02%; pH = 6.0–7.2; 12 days	[59]
24	WH + MAW[2]	64.9%	3:8:9 (pig dung: WH: Poultry droppings)	307 L/ kg		pH = 6.5; TS = 9.09%; 52 days	[60]
25	WH + MAW	62.14%	2:2:1 (WH: cow dung: poultry dropping)			0.02 m	[61]
26	WH + MAW			0.255 kg/m^3	OLR of 1.5 kg/m^3 yielded most biogas	36–37°C; TS = 9.98%; 60 days pH = 5.0–7.4	[62]
27	WH + animal waste	68%	3:7 (WH: animal waste)	14.09 L/ kg	Increasing temperature from 24 to 32 increased production by 186%	24°C	[63]
28	WH + animal waste + others		4:4:2 (waste WH: cow manure)	60 ppm CH_4 10,744 ppm		21 days; size = 2 cm	[64]
29	WH + animal waste		C/N = 20/1 5:3:2 (Prosopis juiflora pods: Duckweed: WH	96.6 L/ kg			[65]

S/N	Starting material	CH_4 yield	Substrate mixing ratio/ concentration	Biogas yield	Observation	Experimental condition	Ref.
30	WH + animal wastes + others			1 L/day		35°C; size = 3–5 cm; TS = 5.6% OLR[3] = 50 g/L	[66]
31	WH + animal wastes + others			273.3 L/kg		40 days	[67]
32	Phytoremediation		C/N 26.9	5195 m^3			[68]
33	Phytoremediation			23,650 cc/kg dry weight	Growing in 20% effluent increased production	35°C 21 days	[69]

[1]*MW = municipal waste.*
[2]*MAW = multiple animal wastes.*
[3]*OLR = organic load ratio.*

Table 1.
Recent studies on generating biogas (CH_4) from water hyacinth (WH) or water hyacinth-based (co-) digestion.

and wells used for sanitation and domestic purposes [82]. Poultry and livestock wastes often contain high concentrations of human pathogens, spilled feed, bedding materials, fur, wastewater, feed residues, feces, and urine. Therefore, the waste should be effectively managed to minimize environmental and public health risks. Such practices might result in acute gastrointestinal upset (e.g., nausea, diarrhea, and vomiting). Also, contact with affected surface waters during recreational activities can cause skin, ear, or eye infections.

4.1 Recent advances with WH only

Some researchers have investigated biogas generation from WH, either solely or co-digested with other waster materials (**Table 1**). Being tagged as a waterway menace, WH has been identified as a substrate for economically feasible biogas production [83, 84].

The effect of substrate concentration, particle size, and incubation period of dry WH shoots (WHS) and whole WH (WWH) plants on biogas production has been reported [37]. The CH_4 yield increased with substrate concentration till the sixth day (25 g/L) before declining. WHS consistently had a higher CH_4 yield than WWH, especially for every particle size. Recently, Syafrudin et al. [38] evaluated the optimization of biogas production using liquid anaerobic digestion. They used central composite and complete factorial design to determine the optimal values of enzyme concentration, C/N ratio, and total solid that generates the highest biogas volume. The optimum conditions for the C/N ratio were within 30–40 and 6% of the enzyme, with no significant effect of total solids. In another research, Patil et al. [40] chopped and ground WH to a fine paste and mixed with water in five ratios to evaluate the optimal level of dilution to produce the highest volume of methane. They reported that the slurry with WH 1:4 water had the highest volume of gas.

The effect of microwave pretreatment of fresh and dried WH on biogas production was also studied [42]. It was observed that the optimum condition is 560 W and 9 min contact time on fresh WH. However, in these conditions, CH_4 production is inhibited. In addition, Rozy et al. [43] studied how various parameters affected biogas production rate and volume. Their maximum biogas yield was achieved at 45°C and a pH of 7, with 1 cm particle size and 40% inoculum concentration and 0.2 mM of $MnCl_2$. Later, a study on the effect of organic (citric) acid pretreatment of WH on biogas production was carried out [44]. Later, response surface methodology was used to optimize the pretreatment parameters. About 76% increase in biogas yield was achieved. For optimum utilization of WH biomass, Hudakorn et al. [48] evaluated the production of biogas and biomass pellets from WH. They stated that, although biogas production commenced from the first day, flammable biogas didn't start to yield till the 10th day.

4.2 Recent advances with co-digested WH

4.2.1 WH + municipal wastes

Nugraha et al. [45] studied the effect of food to microbial (F/M) ratio on biogas yield from WH. They stated that the optimum F/M ratio and TS level were 10.0 and 6.76%, respectively. They concluded that biogas production reduces inversely with the F/M ratio. The same year, Ukwuaba [46] evaluated the performance of biogas yield from co-digesting kitchen wastes and WH. Temperature was identified as the optimal parameter. The highest and lowest gas pressure was observed at the 25th and 37th days, respectively. Previously, Hernandez-shez et al. [47] had investigated the potential of generating biogas from co-digesting WH with fruit and vegetable waste. They optimized the biogas production in terms of total solids concentration. Co-digestion increased the biogas produced. A total solid concentration of 80:20 (WH/food waste), corresponding to a C/N ratio of 20, was the optimal condition to avoid pH correction. However, for a continuous co-digestion, they recommended an organic loading rate of 2 kg VS m^{-3} d^{-1} and 15 days retention time.

4.2.2 WH + poultry droppings

Some co-digestion of WH with poultry droppings has been carried out. Ojo et al. [52] studied the best mix of WH with poultry manure (PM) that produces maximum biogas. The authors calculated for the optimum biogas production rate, a factor of the data collected using the following equation:

$$G^1{}_{max} = -abc[1-c]^{c-1} \tag{7}$$

where $G^1{}_{max}$ = biogas production rate, a = ultimate biogas production, b = pseuso-biogas production velocity (rate constant), c = shape factor.

They observed that mixing WH and PM at 2:8 produced the highest volume of biogas. Furthermore, the volume of biogas produced increases slightly with temperature. Also, the highest biogas yield was observed on the 18th day. It was concluded that 2 WH: 8 PM is the best-aided WH digestion mix in daily biogas production, a cumulative volume of biogas produced, and a maximum biogas production rate. Elsewhere, Patil et al. [41] studied the effect of different pretreatment on biogas yield from WH. Notably, alkali treatment had no significant effect on the biogas produced from WH blended with poultry waste.

4.2.3 WH + cow dungs

Cow dung is a popular co-stock material for WH biodigestion is a popular one. Nugraha et al. [55] used response surface methodology (RSM) to study the optimization of biogas production by solid-state anaerobic digestion to discover the optimum total solids (TS), C/N, and microbial consortium (MC) for biogas production from a mixture of WH and cow dung. They then discovered that TS and MC had the most and least effect on biogas yield, respectively. The maximum biogas yield was obtained at TS concentration range 5–10%, C/N of 32.09, and MC of 6%. Somewhere else, Adegunloye et al. [58] evaluated the optimal ratio of variation of WH to pig dung to generate the maximum methane amount.

The ambient temperature affected the temperature in the digester as the temperature in the digester was higher than the ambient temperature by 1–3°C. The authors observed that 1:3 of WH to pig dung produced the highest amount of CH_4. In another report, Jayaweera et al. [39] evaluated the biogas production from WH grown under different nitrogen concentrations. The author carried out this study for four months at mesophilic temperatures using batch-fed anaerobic reactors. WH was grown in various folds of total nitrogen then co-digested with CD. They mentioned that WH roots contain high fiber and lignin content, thus making them unsuitable as a substrate. They recommended a retention time of 27–30 days for optimum results.

A process by which volatile fatty acids (VFAs) were extracted from WH and the VFAs laden slurry was developed [56]. The extracts were then used as a feed supplement to the conventional biogas digesters. The authors discussed that WH contains 60 g/kg of TS, requiring a large digester for significant biogas production. The VFAs were extracted by charging acid-phase reactors with a mixture of WH and cow dung slurry. The reactors were aerated and the pH kept within 5.5–7.0 to enhance acidogenic bacteria growth but that of methanogenic bacteria. **Figure 2** is a pictorial explanation of the experiment. For the same TS input, the VFA supplemented the feed, yielding 22% higher biogas amount. However, no significant changes happened to methane yield.

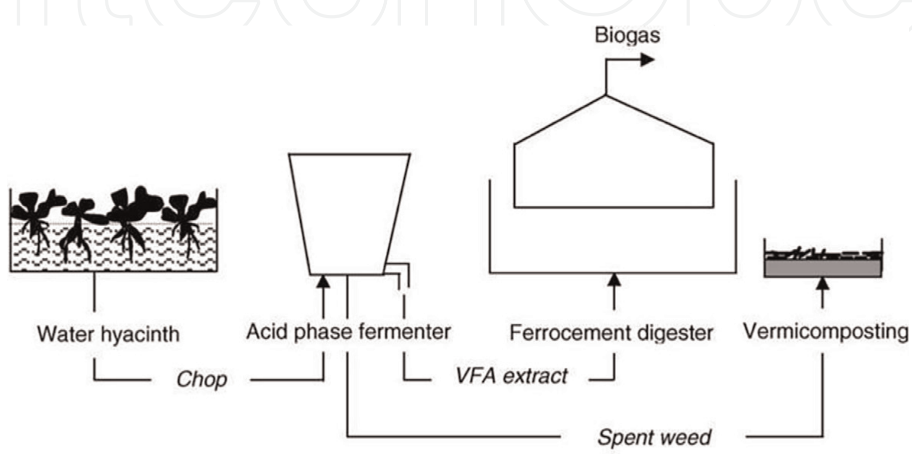

Figure 2.
Schematic representation of the process developed by the authors [56].

Eltawil et al. [85] studied the effect of stirring, dry oxidation, and water scrubbing processes on biogas quality from different substrates. Using five digesters equipped with handle stirrers (**Figure 3**), the gas produced from the digester was flushed through scrubbers to reduce H_2S and CO_2 concentrations of the biogas. They observed that stirring increased the biogas production rate by 45% for WH and cow dung mixtures but did not significantly impact the CH_4 volume of the biogas. We gathered that water scrubbing and dry oxidation removed 95% CO_2 and 97% H_2S. Therefore, this technology is recommended for developing countries where low-cost technology is needed.

Similarly, Akinnuli et al. [59] studied the performance of pig dung and WH for biogas production. The output gas was passed through KOH and anhydrous $CaCl_2$ to remove CO_2 and moisture, respectively. The authors stated that mixing pig dung and water hyacinth in the ratio 1.4:1 was optimum for biogas production. They recommended the digestion be carried out during the summer because low temperatures lead to low biogas generation. Elsewhere, a fixed dome digester was designed for biogas production using cow dung and WH (**Figure 4**) [57]. The digester is a semi-batch reactor composed of a fermentation chamber, feed and digestate pipes and, a

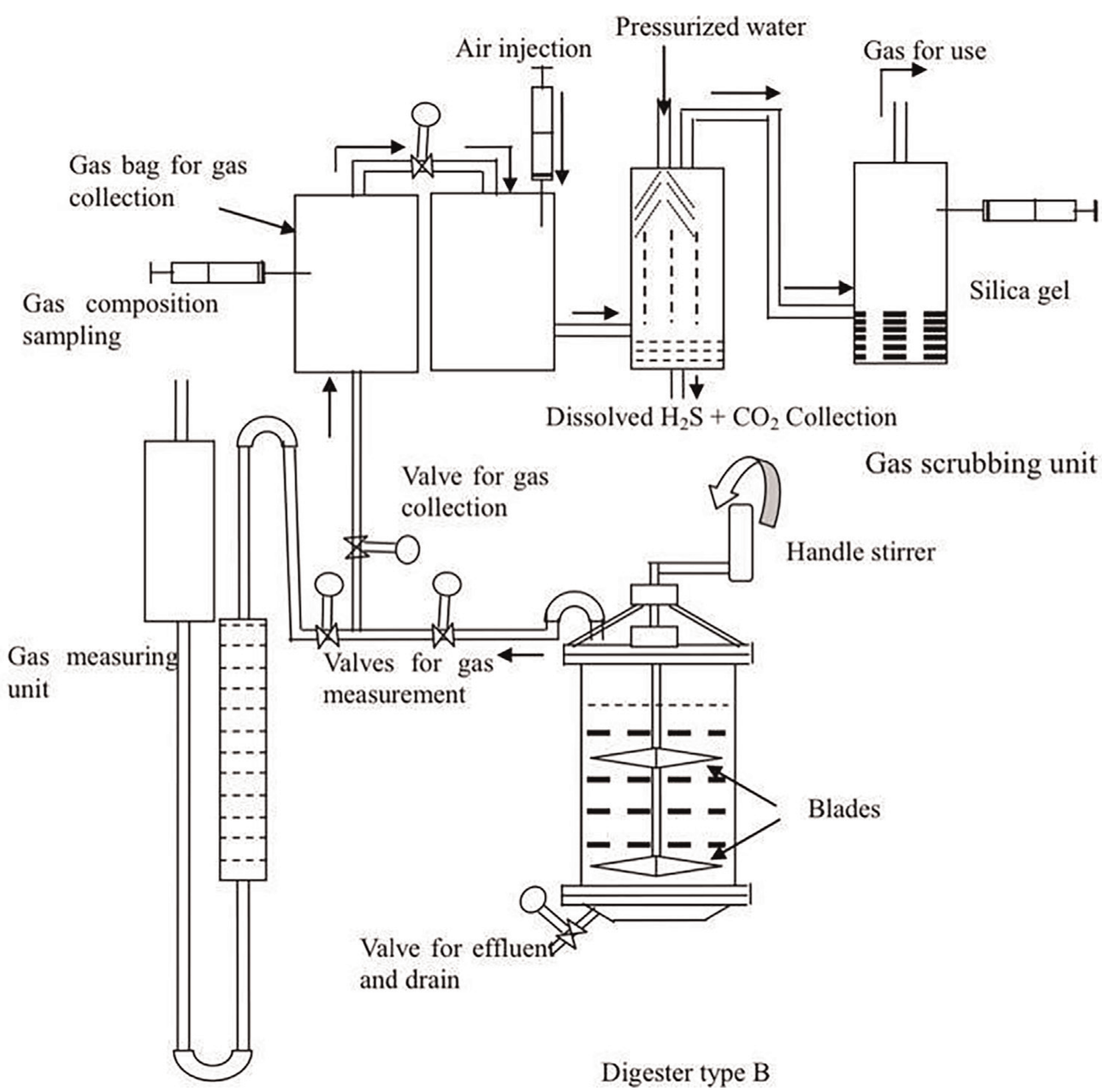

Figure 3.
Schematic diagram of the digester with stirring blade [85].

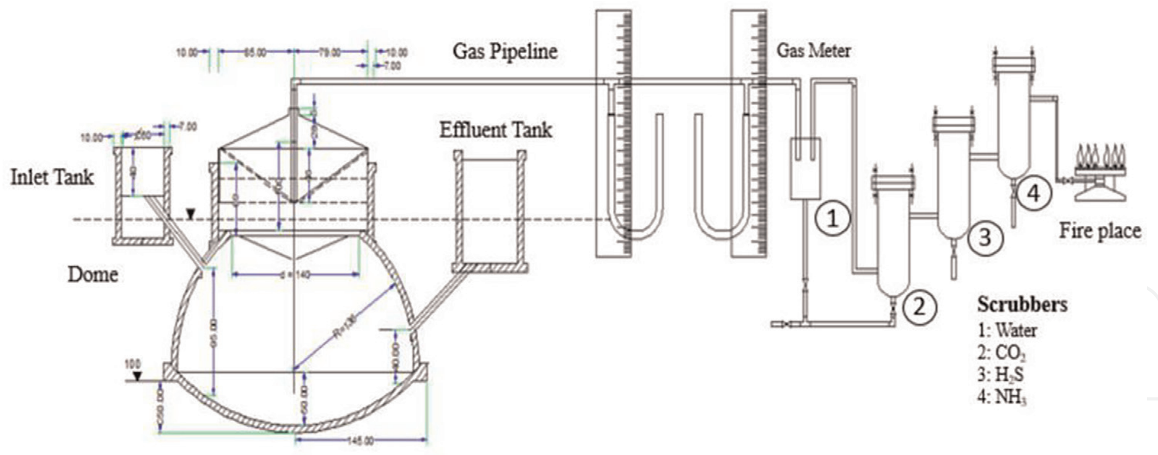

Figure 4.
Schematic diagram of fixed dome digester [57].

fixed dome on top for biogas storage. This configuration was recommended as a cheaper alternative for natural gas production.

4.2.4 WH + multiple animal wastes

Akindele et al. [60] reportedly co-digested pig dung, poultry droppings, and WH anaerobically. Lignocellulosic materials and animal manure co-digestion enhanced digestibility, biogas production, and equipment utilization. The respective mixing ratio of 3:9:8 was optimum for methane yield. Also, no gas production in the first four days as the enzymes adapt to a new environment. CH_4 production lapsed from 8th to 16th day. The biogas production increased with fermentation until the 40th day, with the highest biogas production observed on the 52th day.

Earlier, Fadairo et al. [61] co-digested WH with cow dung and poultry droppings. Their optimum mixing ratios were 2:2:1 and 1:1:0. The lower the WH dosage, the lower the biogas generated. However, the substrate containing WH alone produced the least biogas. Cow dung influenced biogas production than poultry droppings, attributed to the ammonium ions in the latter.

The effect of Organic Loading Rate (OLR) on biogas production systems has also been researched [62]. The rate of adding feedstock required alteration for optimal growth of methanogens, which directly influence biogas produced. The authors noted that direct charging above 1.5 kg/m^3 inhibits the growth of the methanogens. Recently, the co-digestion of (WH) biomass with ruminal slaughterhouse waste (RSW) was evaluated [63]. The highest and lowest biogas yields were with the substrate of solely slaughterhouse waste and WH, respectively. Also, the co-digestion of the waste with WH (5–50%) significantly reduced the retention time by 26 days, whereas if the proportion is >50%, no further impact on retention time will occur. The study recommended co-digestion of 30% waste and 70% WH at 32°C.

In some cases, WH and animal wastes are dosed with other waste materials. Sa’adiah et al. [64] evaluated biogas production from co-digesting Tofu waste, WH, and cow manure. They observed that adding more WH inhibited the production of biogas. They then recommended that mixing WH, tofu, and CD at 2:4:2 for optimal biogas production. Also, Prabhu et al. [65] investigated the anaerobic co-digestion of *Prosopis juliflora* pods with WH, dry leaves, and cow manure, modeled the biogas production kinetics using a modified Gompertz equation to examine the cumulative methane production (Eq. (8)).

$$Y = M * exp\left\{-exp\left[\frac{Rm * e}{M}(\lambda - 1) + 1\right]\right\} \quad (8)$$

where Y = cumulative methane production (L at time t), M = maximum methane production potential (L-CH_4), Rm = maximum methane production rate (L-CH_4/d), λ = Lag phase time (day), E = constant (2.71).

The authors noticed that methane composition was higher in biogas yielded by WH-rich mixtures than other mixtures. E.g, WH + dry (2:3) achieved the maximum methane yield of 80%. The coefficient of determination (R^2) between the experimental data and the model ranged as 0.991–0.999.

Moreover, Shah et al. [66] explored the potential of three plants (WH, giant reed, and maize) and poultry waste for biogas generation, using WH with 13% hemicellulose and poultry waste as inoculum. WH had the highest volatile solids, soluble solids and, a better C/N ratio. Thus, it was a relatively superior biogas substrate. The highest biogas yield occurred on the 11th day. From the four substrates, WH contributed the highest to biogas production. Likewise, Otaraku et al. [86] modeled the cumulative biogas produced from sawdust, cow dung, and WH. They concluded that the polynomial model best fitted the cumulative biogas production at any given day, with $R^2 > 0.9$. Similarly, the potential of biogas production from mixtures of WH, cassava peels, and cow dung using standard microbial techniques has been reported [67]. The highest total biogas yield from co-digesting the three substrates was noted. It was concluded that the prescribed treatment combinations could be facilitated with or without starter culture.

4.2.5 WH + other biomasses

To co-digest WH with other biomasses, Ogunwande et al. [49] constructed biodegradation and maximum biogas yield models based on first-order kinetics to describe and predict maximum biogas yields from the co-digestion of duckweed (DW) and WH. They made three assumptions: there was a correlation between the volatile solid and degradation of biogas yield at any time; a certain quantity of volatile solids in the substrates was recalcitrant to degradation within the retention time allowed; there was no lag time before the beginning of volatile solids degradation. They noted that biogas production started within the first day of digestion. The following biodegradation model was provided:

$$C_t = (C_0 – C_e)\ e^{-kt} + C_e \text{ at } 0 \leq t \quad (9)$$

where C_0 is VS concentration in the substrates at the beginning of the experiment (%, db), C_t is the VS concentration in the substrates at any moment (%, db), t is the time, k is the VS degradation rate constant based on the quantity of VS in the substrate (D^{-1}), C_e is the remnant VS concentration after retention time (%, db). Also, the researchers provided a biogas yield model equation as follows:

$$Y_t = Y_m\left(1 - e^{-kt}\right) \quad (10)$$

where Y_t is the biogas yield at time t and Y_m is the maximum biogas yield.

Elsewhere, Bhui et al. [50] explored the role of volatile fatty acids (VFAs) in WH and Salvinia plant digestion. The biogas production from both plants was highest at an inoculum to substrate ratio of 3:1. It was concluded that acetonic, propionic, and butyric acid were the common VFAs found in the plants that played a major role in biogas production. In the same year, the effects of hydrothermal pretreatment on biogas yield were investigated [51]. A dramatic surge in biochemical oxygen demand (BOD) occurred after the first 30 min of the pretreatment. The increasing BOD revealed that the microbes have larger access to cellulose, a substrate for biogas production. The biogas yield rate started to increase at 30 min of pretreatment, peaking 60 min. Longer hydrothermal pretreatment could reduce the methane yield. Also, the WH:buffalo dung had no significant effects on biogas yield without hydrothermal pretreatment. They recommended a 1:2 WH and cow dung mixing ratio for optimum biogas yield.

4.3 Phytoremediation with WH

Phytoremediation of polluted waster using WH has been researched widely [87]. However, some researchers have delved into adopting post-phytoremediation WH biomass for biogas generation. Singhal et al. [69] co-digested WH and channel grass used to phytoremediate paper mill and distillery factory effluents for biogas production. The plants grown in the effluents were chopped, sun-dried, and oven-dried at 60°C, before pulverizing to fine particles. It was then mixed with cow dung slurry and digested. The digester feed used for phytoremediation produced more biogas than pristine ones. Likewise, the effect of temperature and feedstock size on biogas production of WH used for phytoremediation was reported [88]. It was observed that improved biodegradation of organic matter occurred at high temperatures. Therefore, the digestion of WH should be done at thermophilic conditions with smaller particle size. Similarly, Kumar et al. [68] assessed the biogas production potential of WH that was initially used for phytoremediation of sugar mill effluent. They concluded that the biomass had high potential for biogas production than virgin counterparts.

5. Conclusions and recommendations

The invasive presence of water hyacinth (WH) on our waterways often hinders numerous socioeconomic, agricultural, and ecological processes, tagging the macrophyte an environmental nuisance. However, we have identified that it has some inherent benefits when exploited appropriately. WH is potential biomass for biogas production, and this fact has been adequately studied.

Biogas generation from WH is temperature-dependent, taking place between 25 and 50°C, provided the temperature is kept steady at ± 2°C because methanogens are sensitive to abrupt temperature change. Also, pH can be used as a performance indicator due to acetogenesis bacteria's pH requirement of >5.0 pH, while methanogens require pH in the range of 6.2–8.0 to form CH_4. Overall, WH aids some other biomass biogas generation potential while it retards some others. By co-digesting Salivinia grass and WH at 1:0.5, the highest volume of biogas (406 L/kg VS) generated was reported, whereas co-digestion with pig dung generated the highest CH_4 content (88.3%).

Moreover, co-digesting WH with cow dung (most popularly researched) produced more biogas than with poultry droppings and buffalo dung. Although homogenization aids biogas yield by 50%, it showed no significant effect on CH_4 content. Also, in most cases, increasing C/N and F/M ratios inhibits CH_4 formation. Optimally performing wet scrubbers and dry oxidation for cleanup could remove up to 95% CO_2 and 97% H_2S from the raw biogas generated. It was also identified that digesting WH shoots without the roots could up biogas yield significantly.

Finally, because hydrothermal pretreatment before digestion has recently been identified to enhance biogas generation, we recommend that the effects of various pretreatments for methane generation from WH be further researched.

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References

[1] Demirbas A, Ozturk T. Anaerobic digestion of agricultural solid residues. International Journal of Green Energy. 2005;**1**:483-494

[2] Deublein D, Steinhauser A. Biogas from Waste and Renewable Resources: An Introduction. Weinheim, Germany: Wiley-VCH; 2008

[3] Maile OA, Tesfagiorgis HB, Muzenda E. Factors influencing chemical absorption of CO_2 and H_2S in biogas purification: A review. In: Proceedings of the World Congress on Engineering and Computer Science 2015 Vol II WCECS 2015. San Francisco, USA: Newswood Limited; October 21–23, 2015

[4] Lawal AK, Ajuebor FN, Ojosu JO. Characteristic of piggery wastes feeds stock for determination of design parameters to biogas digester plant. Nigerian Journal of Research and Review in Science. 2001;**2**:193-198

[5] Ortega M. Installation of a Low-Cost Polyethylene Biodigester. Inter-American Institute for Cooperation on Agriculture (IICA); 2009. Available from: http://www.iica.int

[6] Ofoefule AU. Investigation of the biogas production potentials of Bambara nut chaff (Vigna Subterranea). Advances in Applied Science Research. 2011;**2**(2):55-61

[7] Ilaboya IR, Asekhame FF, Ezugwu MO, Erameh AA, Omofuma FE. Studies on biogas generation from agricultural waste: Analysis of the effects of alkaline on gas generation. World Applied Sciences Journal. 2010;**9**(5): 537-545

[8] Rabah AB, Baki AS, Hassan IG, Musa M, Ibrahim AD. Production of biogas using abattoir waste at different retention time. Science World Journal. 2010;**5**(4):23-26

[9] Itodo IN, Agyo GE, Yusuf P. Performance evaluation of a biogas stove for cooking in Nigeria. Journal of Energy in Southern Africa. 2007;**18**(3):14-18

[10] Ezekoye VA, Okeke CE. Design, construction and performance evaluation of plastic bio-digester and the storage of biogas. The Pacific Journal Science and Technology. 2006;**7**:176-184

[11] Ilori MO, Adebusoye A, Lawal AK, Awotiwon OA. Production of biogas from banana and plantain peels. Advances in Environmental Biology. 2007;**1**:33-38

[12] Adeyanju AA. Effect of seeding of wood-ash on biogas production using pig waste and cassava peels. Journal of Engineering and Applied Science. 2008;**3**:242-245

[13] Babel S, Sae-Tang J, Pecharaply A. Anaerobic co-digestion of sewage and brewery sludge for biogas production and land application. International Journal of Environmental Science and. Technology. 2009;**6**:131-140

[14] Abbey AT. Biogas in Uganda: A new experience. Leisa. 2005;**21**(1):13-17

[15] AGAMA Energy. Employment Potential of Renewable Energy in South Africa. Study Commissioned by Sustainable Energy and Climate Change Partnership and Earthlife Africa. Zambia: AGAMA; 2003

[16] Omer AM, Fadalla Y. Biogas energy technology in Sudan: Technical note. Renewable Energy. 2003;**28**:499-507

[17] Ersahin MV, Gomec CV, Dereli RK, Arikan O, Ozturk I. Biomethane production as an alternative: Bioenergy source from codigesters treating municipal sludge and organic fraction of municipal solid wastes. Journal of Biomedicine and Biotechnology. 2011;**8**: 1-8

[18] De Vrije T, De Haas GG, Tan GB, Keijsers ERP, Claassen PAM. Pretreatment of Miscanthus for hydrogen production by *Thermotoga elfii*. International Journal of Hydrogen Energy. 2002;**27**(11-12):1381-1390

[19] Panagiotopoulos IA, Bakker RR, Budde MAW, De Vrije T, Claassen PAM, Koukios EG. Fermentative hydrogen production from pretreated biomass: A comparative study. Bioresource Technology. 2009;**100**(24):6331-6338

[20] Bekkering J, Broekhuis A, Van Gemert W. Optimisation of a green gas supply chain: A review. Bioresource Technology. 2010;**101**:450-456

[21] Holm-Nielsen J, Al Seadi T, Oleskowics-Popiel P. The future of anaerobic digestion and biogas utilization. Bioresource Technology. 2009;**100**:5478-5484

[22] Jantsch TG, Matttiason B. An automated spectrophotometric system for monitoring buffer capacity in anaerobic digestion processes. Water Research. 2004;**38**:3645-3650

[23] Nan LB, Trably E, Santa-Catalina G, Bernet N, Delgenes J-P, Escudie R. Biomethanation processes: New insignts on the effect of a high H_2 partial pressure on microbial communities. Biotechnology for Biofuels. 2020;**13**:141

[24] Li Y, Yan XL, Fan JP, Zhu JH, ZhouW B. Feasibility of biogas production from anaerobic co-digestion of herbal-extraction residues with swine manure. Bioresource Technology. 2011; **102**:6458-6463

[25] Sambusitu C. Physical, chemical and biological treatments to enhance biogas production from lignocellulosic substrates [PhD thesis]. Politecnico Di Milano: Department of Civil and Environmental Engineering; 2013

[26] Lozano CJ, Mendoza MV, de Arango MC, Monroy EF. Microbiological characterization and specific methanogenic activity of anaerobe sludges used in urban solid waste treatment. Waste Management. 2009; **29**(2):704-711

[27] Franke-Whittle IH, Goberna M, Pfister V, Insam H. Design and development of the ANAEROCHIP microarray for investigation of methanogenic communities. Journal of Microbiological Methods. 2009;**79**(3): 279-288

[28] Odeyemi O. Biogas production. In: Proceeding of the fifth Annual Conference of the Nigerian Society of Microbiology; 2nd–6th Dec, 2001; Ado Ekiti. pp. 17-24

[29] Poliafico M. Anaerobic digestion: Decision support software [masters thesis]. Cork Institute of Technology: Department of Civil, Structural and Environmental Engineering

[30] Nettmann E, Bergmann I, Klocke M. Methanogene Archaea in landwirtschaftlichen Biogasanlagen. In Bayerische Landesanstalt für Landtechnik editor. Internationale Wissenschaftstagung Biogas Science. Freising: ES-Druck; 2009. pp. 303-318

[31] Jenner M. The Biotown, USA Sourcebook of Biomass Energy (Internet). Indiana: Indiana State

Department of Agriculture and Reynolds; 2006. Available from: http://www.in.gov/biotownusa/pdf/Biotown_Sourcebook_040306.pdf [Accessed: March 31, 2015]

[32] Tingi K, Lee K, Worley J, Risse M. Anaerobic digestion of poultry litter: A review. Applied Engineering in Agriculture. 2010;**26**(4):677-688

[33] Erickson LE, Fayet E, Kakumanu BK, Davis LC. Anaerobic Digestion. National Agricultural Biosecurity Center, Kansas State University, Kansas; 2005

[34] Yen HW, Brune D. Anaerobic co-digestion of algal sludge and waste paper to produce methane. Bioresource Technology. 2004;**98**:130-134

[35] Liu X, Chen Y, Du G, Chen J. Effects of organic matter and initial carbon-nitrogen ratio on the bioconversion of volatile fatty acids from sewage sludge. Journal of Chemical Technology and Biotechnology. 2008;**83**:1049-1055

[36] Oyeleke SB, Onigbajo HO, Ibrahim K. Degradation of animal wastes (cattle dung) to produce methane (cooking gas). In: Proceedings of the eighth annual Conference of Animal Science Association of Nigeria (ASAN). Lagos: Journalijar; 2003. pp. 168-169

[37] Katima JHY. Production of biogas from water hyacinth: Effect of substrate concentration, particle size and incubation period. Tanzania Journal of Science. 2001;**27**:109-119

[38] Syafrudin, Nugraha WD, Matin HHA, Margaretha F, Budiyono. Optimization of biogas production from water hyacinth by liquid anaerobic digestion (L-AD) using response surface methodology. IOP Conference Series: Materials Science and Engineering. 2020;**845**:012046

[39] Mahesh W, Jayaweera JAT, Dilhani RKA, Kularatne SLJ, Wijeyekoo. Biogas production from water hyacinth (Eichhornia crassipes (Mart.) Solms) grown under different nitrogen concentrations. Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering. 2007;**42**(7):925-932

[40] Patil JH, Lourdu MA, AntonyRaj, Gavimath CC. Impact of dilution on biomethanation of fresh water hyacinth. International Journal of Chemical Sciences and Applications. 2011;**2**(1):86-90

[41] Patil JH, Lourdu MA, AntonyRaj, Gavimath CC. Study on effect of pretreatment methods on biomethanation of water hyacinth. International Journal of Advanced Biotechnology and Research. 2011;**2**(1):143-147

[42] Siswo S, Budiyono, Marian DT. The effect of microwave power and heating time pretreatment on biogas production from fresh and dried water hyacinth (Eichhornia Crassipes). American Institute of Physics. 2015;**1699**:050018

[43] Rozy R, Dar A, Urmila GR. Optimization of biogas production from water hyacinth (*Eichhornia crassipes*). Journal of Applied and Natural Science. 2017;**9**(4):2062-2067

[44] Tantayotai P, Mutrakulchareon P, Tawai A, Roddecha S, Sriariyanun M. Effect of organic acid pretreatment of water hyacinth on enzymatic hydrolysis and biogas and bioethanol production. IOP Conference Series: Earth and Environmental Science. 2019;**346**:012004

[45] Nugraha WD, Syafrudin S, Pradita LL, Matin HHA, Budiyono.

Biogas production from water hyacinth (Eichhornia Crassipes): The effect of F/M ratio. IOP Conference Series: Earth and Environmental Science. 2018;**150**: 36-39

[46] Ukwuaba SI. Performance evaluation of biogas yields potential from co-digestion of water hyacinth and kitchen waste. European Journal of Engineering Research and Science. 2018;**3**:4

[47] Hernández-Shek MA, Cadavid-Rodríguez LS, Bolaños IV, Agudelo-Henao AC. Recovering biomethane and nutrients from anaerobic digestion of water hyacinth (Eichhornia crassipes) and its co-digestion with fruit and vegetable waste. Water Science & Technology. 2018;**73**:2

[48] Teerasak H, Noppong S. Biogas and biomass pellet production from water hyacinth. Energy Reports. 2020;**6**: 532-538

[49] Ogunwande GA, Adanikin BA, Adesanwo OO. Comparative evaluation and kinetics of biogas yield from duckweed (lemna minor) co-digested with water hyacinth (*Eichhornia crassipes*). Ife Journal of Science. 2018;**20**:3

[50] Mathew AK, Bhui I, Banerjee SN, Goswani R, Chakranorty AK, Shome A, et al. Biogas production from locally available aquatic weeds of Santiniketan through anaerobic digestion. Clean Technologies and Environmental Policy. 2015;**17**:1681-1688

[51] Yuhelsa P, Dewi M, Teguh K. Study of biogas production rate from water hyacinth by hydrothermal pretreatment with buffalo dung as a starter. Waste Technology. 2014;**2**(2):26-30

[52] Ochuko MO, Josiah OB, Adebisi OA, Olurinde L, Adelodun AA. Co-digestion of water Hyacinth and poultry manure for improved biogas yield. ABUAD Journal of Engineering Research and Development (AJERD). 2020;**2**(1):42-48

[53] Njogu P, Kinyua R, Muthoni P, Nemoto Y. Biogas production using water hyacinth (*Eicchornia crassipes*) for electricity generation in Kenya. Energy and Power Engineering. 2020;**7**:209-216

[54] Barua VB, Kalamdhad AS. Biogas production from water hyacinth in a novel anaerobic digester: A continuous study. Process Safety and Environmental Protection. 2019;**127**:82-89

[55] Nugraha WD, Syafrudin SAT, Abdul Matin HH, Budiyono. Optimization of biogas production by solid state anaerobic digestion (SS-AD) method from water hyacinth with response surface methodology (RSM). E3S Web of Conferences. 2018;**73**:01016

[56] Ganesh PS, Ramasamy EV, Gajalakshmi S, Abbasi SA. Extraction of volatile fatty acids (VFAs) from water hyacinth using inexpensive contraptions, and the use of the VFAs as feed supplement in conventional biogas digesters with concomitant final disposal of water hyacinth as vermicompost. Biochemical Engineering Journal. 2005; **27**:17-23

[57] Ajieh MU, Ogbomida TE, Onochie UP, Akingba O, Kubeyinje BF, Orerome OR, et al. Design and construction of fixed dome digester for biogas production using cow dung and water hyacinth. African Journal of Environmental Science and Technology. 2019;**14**(1):15-25

[58] Adegunloye DV, Olosunde SY, Omokanju AB. Evaluation of ratio variation of water hyacinth (*Eichhornia Crassipes*) on the production of pig dung biogas. International Research Journal of Biological Sciences. 2013;**2**(3):44-48

[59] Akinnuli BO, Olugbade TO. Development and performance evaluation of piggery and water hyacinth waste digester for biogas production. International Journal of Engineering and Innovative Technology (IJEIT). 2014;**3**(10):271-276

[60] Akindele OO, Olusola AA. Evaluation of biogas production from co-digestion of pig dung, water hyacinth and poultry droppings. Waste Disposal & Sustainable Energy. 2019;**1**(4):271-277. DOI: 10/1007/s42768-019-00018-8

[61] Fadairo AA, Fagbenle RO. Biogas production from water hyacinth blends. In: Proceedings from the 10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics. Florida; 2014

[62] Orhorhoro EK, Ebunilo PO, Sadjere GE. Effect of organic loading rate (OLR) on biogas yield using a single and three-stages continuous anaerobic digestion reactors. International Journal of Engineering Research in Africa. 2018;**39**:147-155

[63] Omondi EA, Gikuma-Njuru P, Ndiba PK. Anaerobic co-digestion of water hyacinth (*E. crassipes*) with ruminal slaughterhouse waste for biogas production. International Journal of Renewable Energy Development. 2019;**8**(3):253-259

[64] Sa'diah S, Putra MD. Biogas production from wastes of Tofu Industry with effects of water hyacinth and cow manure additions. IOP Conference Series Materials Science and Engineering. 2019;**543**:012097

[65] Prabhu AV, Manimaran R, Raja SA, Jeba P. Biogas production from anaerobic co-digestion of Prosopis juliflora pods with water hyacinth, dry leaves, and cow manure. Energy Sources Part A: Recovery, Utilization, and Environmental Effects. 2019;**42**(3):375-386

[66] Ali-Shah F, Mahmood Q, Rashid N, Pervez A, Iqbal A, Shah MM. Anaerobic digestion of water hyacinth, giant reed, maize and poultry waste for biogas generation. EC Agriculture. 2015;**2**(2):277-284

[67] Asikong BE, Epoke JA, Bassey E, Antai EE, Eja ME. Potentials of biogas generation from mixture of three substrates, water hyacinth, cassava peels and cow dung- Wh+Cp+Cd. Chemical and Process Engineering Research. 2013;**17**:1-11

[68] Kumar V, Singh J, Kumar P. Adding benefits to phytoremediation of sugar mill effluent by growing water hyacinth (*Eichhornia crassipes*): Evaluation of biomass for biogas production. Archives of Agriculture and Environmental Science. 2018;**3**(3):275-288

[69] Singhal V, Rai JPN. Biogas production from water hyacinth and channel grass used for phytoremediation of industrial effluents. Bioresource Technology. 2003;**86**:221-225

[70] Parawira W, Mshandete AM. Biogas technology research in selected sub-Saharan African countries: A review. African Journal of Biotechnology. 2009;**8**:116-125

[71] Lethomäki A, Viinikainen TA, Rintala JA. Screening boeral energy crops and crop residues for methane biofuel production. Biomass and Bioenergy. 2008;**32**:541-550

[72] Carlsson M, Uldal M. Substrate handbook for biogas production. Report SGC. 2009;**200**:21

[73] Yadvika S, Sreekrishnan TR, Kohli S, Rana V. Enhancement of biogas

production from solid substrates using different techniques—A review. Bioresource Technology. 2004;**95**:1-10

[74] Thy S, Preston TR, Ly J. Effect of retention time on gas production and fertilizer value of biodigesters effluent. Livestock Research for Rural Development. 2003;**15**(7):1-24

[75] Arogo JO, Wen Z, Igno J, Bendfeldt E, Collins ER. Biomethane Technology. Virginia Polytechnic Institute and State University, Virginia: College of Agriculture and Life Sciences; 2009. pp. 442-881

[76] Gerardi MH. The Microbiology of Anaerobic Digesters. New Jersey: John Wiley & Sons, Inc; 2003

[77] Karki AB, Shrestha NJ, Bajgain S. Biogas as Renewable Energy. Malmoe: ETDEWEB; 2005

[78] Monnet F. An Introduction to Anaerobic Digestion of Organic Waste (Internet). Remade, Scotland 2003. Available from: http://www.remade.org.uk/media/9102/ [Accessed: August 30, 2013]

[79] Kossmann W, Pönitz U, Habermehl S. Biogas Biogas Digest. Boston: Paques; 2000

[80] Alvarez R, Lidén G. The effect of temperature variation on biomethanation at high altitude. Bioresource Technology. 2008;**99**: 7278-7284

[81] Harikishan SS. Cattle waste treatment and class a biosolid production using temperature phased anaerobic digester. Advances in Environmental Research. 2003;**7**:701-706

[82] Nwanta JA, Onunkwo J, Ezenduka E. Analysis of Nsukka metropolitan abattoir solid waste and its bacterial contents in south eastern Nigeria: Public health implication. Archives of Environmental & Occupational Health. 2010;**65**:21-26

[83] Akinbami JFK, Ilori MOM, Oyebisi TO, Akinwumi IO, Adeoti O. Biogas energy use in Nigeria: Current status, future prospects and policy implications. Renewable and Sustainable Energy Reviews. 2001;**5**:97-112

[84] Ubalua AO. Cassava wastes: Treatment options and value addition alternatives. African Journal of Biotechnology. 2008;**6**:2065-2073

[85] Eltawil MA, Belal EBA. Eval'uation and scrubbing of biogas generation from agricultural wastes and water hyacinth. Misr Journal of Agricultural Engineering. 2009;**26**(1):534-560

[86] Otaraku IJ, Anaele JV. Modelling the cumulative biogas produced from sawdust, cow dung and water hyacinth. International Journal of Advanced Engineering Research and Science. 2020; **7**(3):504-511

[87] Rezania S, Mohanadoss P, Talaiekhozani A, Mohamad S, Md Din MF, Mat Taib S, et al. Perspectives of phytoremediation using water hyacinth for removal of heavy metals, organic and inorganic pollutants in wastewater. Journal of Environmental Management. 2015;**163**:125-133

[88] Xu D. Effect of temperature and feedstock size on biogas production of water hyacinth used for phytoremediation of rural domestic wastewater in Shanghai. Key Project of Science and Technology Commission of Shanghai Municipality. 2010; No. 06DZ12311