Characterization of water hyacinth (*E. crassipes*) from Lake Victoria and ruminal slaughterhouse waste as co-substrates in biogas production

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Abstract

Water hyacinth (*Eichhornia crassipes*), an invasive water weed with a large biomass, poses serious socioeconomic and environmental challenges in fresh water bodies. Efforts to control and remove water hyacinth (WH) can be complemented by biogas production, which, however, requires knowledge of its chemical and nutritional composition. Moreover, co-digestion with other substrates may compensate for possible limitations of its largely lignocellulosic biomass. This study carried out proximate, crude fiber, elemental and biochemical analysis of WH and a co-substrate, ruminal slaughterhouse waste (RSW). The WH had significant concentrations of cellulose, hemicellulose and carbohydrates of 331,200, 231,800 and 447,800 mg/L, respectively, and lesser concentration of lignin of 99,400 g/L that is desirable in biomass for biogas production. Concentrations of C, N, P and K in WH were 15,480, 1654, 51 and 137 mg/L compared to 26,220, 1390, 34 and 7475, respectively, for RSW, which indicated potential for biogas generation. The potassium concentration for WH of 137 mg/L was below the optimum range of 200–400 mg/L while that for RSW of 7476 mg/L was in the inhibitory range. Both biomass exhibited phosphorous deficiency at C/P of 310 and 656 for WH and RSW, respectively, against optimum ratio of 100 and 150 for hydrolysis and acidogenesis stages and methanogenesis stage, respectively. The C/N for WH of 9.4 was at the lower limit for optimal biogas production of 8 mg/L that demarcates potential ammonia toxicity while that for RSW of 18.8 was near the upper limit of 20 mg/L for nitrogen deficiency. Co-digesting the two substrates has the potential for balancing potassium concentrations and the C/N ratios. Trial co-digestion of WH with RSW improved WH gas production demonstrating complementary effect of the two substrates. However, commercialization of the co-digestion would need to establish the optimal mix proportions and methanogenic microbial communities involved in the digestion process.

Keywords Lignocellulose · Biomass · Biogas · Water hyacinth · C/N ratio · Ruminal slaughterhouse waste

1 Introduction

Water hyacinth (*Eichhornia crassipes*), an invasive aquatic weed, has a high growth rate with potential for doubling its population every 5–15 days and producing up to 140 million daughter plants annually [42, 45]. In the past two decades, the weed has invaded and proliferated in Lake Victoria in East African causing major socioeconomic

and environmental disruptions including blockage of fishing grounds, transport routes, and water intakes and increase in waterborne diseases among other challenges [14, 22]. Management and removal of the weed from the lake have been expensive and only partially successful [16]. However, efforts for control and removal of the weed can be complemented by its use as a biomass for biogas production. The lignocellulosic biomass,

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which is non-edible, can be exploited and utilized with less capital-intensive technologies than those for fossil fuels [3]. Consequently, its utilization can mitigate the high reliance on fossil fuel for energy and its associated environmental degradation including climate change [8].

Knowledge of chemical composition of biomass is important in determining biomass conversion into green fuels and other valuable chemicals, which is useful in process commercialization. Lignocellulose biomass from plants is grossly composed of cellulose, hemicelluloses and lignin which are bonded together into microfibrils by covalent bonding, intermolecular bridges and van der Waals' forces [21]. The fiber fraction composition of lignocellulosic material varies among different plants and their harvesting times [27, 38, 44]. Cellulose is typically the most abundant fiber component at 30–70%, while hemicellulose and lignin represent 15–30 and 10–25% for most plant biomass, respectively [27].

Cellulose are linear polymers composed of cellobiose units, a glucose–glucose dimer. The hydrolysis of cellulose releases the individual glucose monomers: the process known as saccharification [19]. Cellulose chains are grouped together to form microfibrils, and the microfibrils are bunched together to form cellulose fibers [1]. Anaerobic cellulolytic clostridia degrade cellulose through the action of an extracellular multienzyme complex—a cellulosome [40]. Hemicellulose is a heterogeneous polysaccharide composed of a series of random branched polysaccharides [41, 46], of which the short branch chains usually contain various polymers such as xylose, mannose, galactose, rhamnose and arabinose [27, 46].

Lignin is a large, complex aromatic heteropolymer present in cell walls that is made of highly cross-linked phenyl propylene polymer. Its proportion varies between plant species making up 25–36% of wood biomass, [5], 9–23% aquatic plants [33], 5–10% grasses [39, 43] and 20–25% modern land plants such as algae [37]. Lignin plays an important role in cell wall structure as a permanent bonding agent among plant cells. Unlike cellulose, lignin cannot be depolymerized to its original monomers. Lignin and hemicellulose form a sheath that surrounds the cellulosic portion of the biomass. This complexity makes it resistant to detailed chemical characterization as well as microbial degradation, thus requiring digestion [7].

Lignocellulosic materials such as energy crops and plant residues are often rich in carbon, but low in nutrient content such as nitrogen, phosphorus and trace elements [38]. A carefully selected co-substrate from slaughterhouse can compensate the limitations of lignocellulosic biomass, facilitate a stable and efficient anaerobic digestion process and enhance biogas production [24].

Slaughterhouses are faced with the challenge of treating and disposing of wastewater and solid wastes, which can amount to as much as 45–50% of the live weights of animals [30]. The waste comprises of rumen content, 56%; inedible fats, 18%; womb, 18%; large intestine, 15%; and udder, 6% [15]. The wastes with the exception of rumen contents are characterized by large organic content composed mainly of animal proteins and fats [6, 10]. Degradation of proteins during anaerobic digestion produces ammonia, which is toxic to methanogenic bacteria in concentrations greater than 80 mg/l [2]. Therefore, anaerobic digestion of slaughterhouse would favor use of rumen contents. Consequently, this study characterized WH and RSW biomasses for evaluation of synergy in co-digestion.

2 Materials and methods

2.1 Overview of methods

This study characterized WH from Lake Victoria and RSW from a slaughterhouse in Nairobi as substrates for biogas productions. Tests carried out included proximate, elemental, fiber content and biochemical analyses. Anaerobic digestion was conducted for WH and RSW separately and in co-digestion for up to 60 days.

2.2 Sampling and sample preparation

Water hyacinth was collected from the shores of Winam Gulf, Lake Victoria, at Kisumu City, coordinates $-0^{\circ}53'9.71''\text{S}$, $34^{\circ}45'2.44''\text{E}$ (Fig. 1a). Fresh, healthy, mature plants were manually sampled about 50 m from the shore on August 2 2017 at about 9 am. The samples were packed in sampling bags before being transported the same day to the University of Nairobi's Environmental Engineering Laboratory in preparation for tests. Fresh WH plants including roots, stems and leaves were chopped to small sizes of 2 cm and allowed to dry under the sun for 7 days. They were then dried in an oven at 60°C for 6 h (e.g., [42]). The oven-dried material was ground to fine particles using a grinding mill. Samples were placed into plastic bags, vacuum-sealed and placed in a refrigerator at 4°C awaiting characterization.

Fresh RSW was collected from Nairobi's Dagoretti Slaughterhouse located in western part of Nairobi City at coordinates $1^{\circ}17'3.71''\text{S}$, $36^{\circ}41'1.98''\text{E}$ (Fig. 1b). The ruminal contents were manually sampled from the slaughterhouse waste yard on August 6 2017 at about 8 am during the slaughtering process. The samples were packed in sampling five litter buckets and immediately transported to the laboratory where they were kept at 4°C awaiting processing and analysis. The samples were homogenized and

Fig. 1 Map showing location of **a** WH sampling point in Winam Gulf, Kisumu, Kenya, and **b** slaughter house waste sampling point, Dagoretti, Nairobi

allowed to dry in the sun for a period of 3 days and then dried in an oven at 60 °C for 6 h (e.g., [42]). Moisture content was determined from weight difference before and after drying. The oven-dried material was ground to fine particles using a grinding mill and placed into plastic bags, vacuum-sealed and stored in a refrigerator at 4 °C awaiting characterization.

2.3 Proximate analysis of dry matter

Proximate analysis of WH dry matter was done to determine the composition of the cell contents, cell wall and the moisture content. The cell contents included crude protein, crude fats, carbohydrates and minerals while the cell wall comprised of crude fiber and ash. Moisture content,

protein, fat, crude fiber and carbohydrates concentrations and ash content were determined following Association of Official Analytical Chemists (AOAC) methods specification 950.46 AOAC [4]. Tests were carried out in triplicate.

Measurement of moisture content of WH was taken by weighing about 2 g of air-dried sample into a crucible and drying it in an oven preheated to temperatures of 105 °C for 1 h. Moisture content was then calculated using the following formula.

$$\text{Moisture (\%M)} = ((W_1 - W_2/W_3)) \times 100 \quad (1)$$

where W_1 = weight of the crucible and the air-dried sample (g), W_2 = weight of the crucible and oven-dried sample (g) and W_3 = weight of the air-dried sample taken (g).

Crude protein in the WH was determined using Kjeldahl method [36]. Raw material, 1 g, was hydrolyzed with 15 mL concentrated sulfuric acid (H_2SO_4) containing two copper catalyst tablets in a heat block (Kjeltec system 2020 digester, Tecator Inc, Herndon, VA, USA) at 420 °C for 2 h. After cooling, distilled water was added to the hydrolysates before neutralization and titration. The amount of total nitrogen in the raw materials was multiplied with both the traditional conversion factor of 6.25 [23] and species-specific conversion factors [20] in order to determine total protein content.

Crude fiber was determined gravimetrically after chemical digestion and solubilization of other materials present in the sample. Approximately 2 g of the sample (W) was extracted by boiling in 200 mL of 1.25% H_2SO_4 for 30 min under reflux condenser. Filtration was done under slight vacuum with Pyrex glass filter and the residue washed to completely remove the acid with boiling water. Approximately 200 mL of boiling 1.25% NaOH was added to the washed residue and boiling done under reflux for another 30 min. Filtration was done using the same glass filter previously used with the acid. The residue was rinsed with boiling water followed by 1% HCL and again washed with boiling water to rinse the acid from the residue. The residue was washed twice with alcohol and thrice with ether. It was then dried in an oven at 105 °C in a porcelain dish to a constant weight (W_1). Incineration was done in a muffle furnace at 550 °C for 3 h, the dish was then cooled in a desiccator, and the final weight (W_2) was taken. Calculations were done as shown:

$$\text{Crude fiber (\%)} = \frac{(W_1 - W_2)}{W} * 100 \quad (2)$$

To determine the ash content in the water hyacinth, 5 g of air-dried sample was put in preconditioned crucibles and the sample was first charred by flame to eliminate organic material before being incinerated at 550 °C in a muffle furnace to the point of white ash. The residue was cooled in desiccators and the weight taken as the ash content. The percentage content of total carbohydrates in the WH was calculated by subtracting the sum of moisture, protein, fat, ash and crude fiber percentages from 100 AOAC [4].

Proximate analysis for crude protein, crude fiber and crude fat, and ash, moisture and carbohydrates for RSW was carried out using the same procedures as those employed for WH biomass.

2.4 Fiber content determination

The composition of lignocellulosic substrates was determined using direct method [29]. Air-dried WH sample of approximately 5 g was boiled in ethanol four times for

15 min, washed thoroughly with distilled water and then kept in oven at 40 °C overnight. The dry sample was weighed (A) and then treated with 24% KOH for 4 h at 25 °C and washed thoroughly with distilled water dried overnight at 80 °C and the dry weight taken as B fraction. The sample again treated with 72% H_2SO_4 for 3 h to hydrolyze the cellulose and then refluxed with 5% H_2SO_4 for 2 h H_2SO_4 was removed completely by washing with distilled water, and the sample was then dried at 80 °C in oven for overnight and dry weight taken as C fraction. The lignocellulosic substrates were then calculated as follows

$$\text{Cellulose} = B - C$$

$$\text{Hemicellulose} = A - B$$

$$\text{Lignin} = C$$

Fiber content determination for RSW was carried out using the same procedures as those employed for WH biomass.

2.5 Elemental analysis

Approximately 3 g of the oven-dried WH sample was digested for 3 h with 20 mL acid mixture prepared from selenium powder, lithium sulfate, hydrogen peroxide and sulfuric acid. The digestion was carried out at 360 °C until the solution and the residue appeared colorless. The contents were diluted with distilled water to a final volume of 50 mL. The digest was then used for the analysis of total Kjeldahl nitrogen, total phosphorous and potassium.

Kjeldahl nitrogen was obtained by titration method using hydrochloric acid (HCl) and computing Kjeldahl nitrogen [36]. Potassium concentration was determined by analyzing the digest on a flame photometer [12, 26], while total phosphorous (TP) was determined by ascorbic acid method [9, 32].

Fixed carbon was determined by first determining volatile solids which involved weighing 1 gm of the sample in a silica crucible with a porous silica cover to avoid oxidation. The sample was then heated for 7 min at a constant temperature of 900 °C inside a furnace. After heating, the crucible was cooled and transferred to a desiccator. The silica crucible was re-weighed after 10 min of cooling. The difference in weight before and after gave the amount of volatile matter in the sample. The fixed-carbon content of the sample was then calculated according to the following formulae [47]:

$$\text{Fixed Carbon (\%)} = 100\% - \text{Ash (\%Dry Basis)} - \text{Volatile Matter (\%Dry Basis)}$$

Elemental analysis for nitrogen (N), phosphorus (P), potassium (K) and carbon (C) for RSW was carried out

using the same procedures as those employed for WH biomass.

2.6 Determination of total solids (TS), volatile solids (VS) and fixed solids (FS)

To determine the fixed and volatile solids for RSW and WH biomass, about 5 g of dried sample was ignited in muffle furnace at 550 °C for 1 h. The sample was cooled in desiccator and weighed. The ignition was repeated for 30 min, cooled and weighed until the weight change was less than 4%. The samples were analyzed in duplicate, and the calculations for fixed and volatile solids were done as follows:

$$\% \text{total solids} = \frac{(A - B)}{C - B} * 100 \quad (3)$$

$$\% \text{volatile solids} = \frac{(A - D)}{A - B} * 100 \quad (4)$$

$$\% \text{fixed solids} = \frac{(D - B)}{A - B} * 100 \quad (5)$$

where *A* is the weight of dried residue + dish, mg, *B* the weight of dish, *C* the weight of wet sample + dish, mg and *D* the weight of residue + dish after ignition, mg.

2.7 Determination of COD, TCOD, SCOD and volatile fatty acids

Chemical oxygen demand (COD) was determined using dichromate method (APHA 1998). About 2 g of the samples (WH or RSW) was placed in culture tube and acidified potassium dichromate digestion solution added, and after mixing, concentrated sulfuric acid was carefully run down inside of the vessel to form an acid layer under the sample-digestion solution layer.

Total COD was run on undiluted samples while soluble COD was run on samples filtered through a 0.45-mm filter before analysis to remove biological interference. TCOD samples were diluted with deionized water in a ratio of 1:5 before analysis. Two milliliters of the samples, for both TCOD and SCOD, was pipetted into a COD digestion reagent vial. The vial was then inverted several times to mix (vial will get hot). The vial was placed in the COD reactor at 150 °C for two hours. The samples were cooled and tested using a spectrophotometer. The chemical oxygen demand values were read in mg/L for both total COD (TCOD) and soluble COD (SCOD).

Determination of volatile fatty acids (VFAs) was done using gas chromatography (GC). The samples were acidified using nitric acid, and then, the VFAs were extracted to diethyl ether phase followed by conversion of VFAs into methyl esters which were then analyzed using GC to obtain derivatives. For quantitative analysis the external standard methodology was used, where calibration standards of five acids: acetic, propionic, butyric, valeric, and caproic, in concentrations ranging from 5 to 1000 mg/ml, were used. The calibration standards were prepared with the same procedure as for samples.

2.8 Anerobic digestion tests

The potency of WH and RSW substrates for biogas production, separately and in co-digestion was evaluated by carrying out anerobic digestion tests. Water hyacinth and RSW were anerobically digested in a laboratory batch reactor operated at 37 °C (Fig. 2). Four sets of the arrangement were prepared, one for WH substrate, another for RSW and the last two for co-digestion of 1:4 and 1:5 RSW: WH ratios as trial proportions. The generated biogas was passed through NaOH solution to remove CO₂ and collected as methane gas through a displacement method. The tests

Fig. 2 Biogas production setup under water bath digester temperature control

were run for 60 days and the cumulative methane generation recorded daily.

3 Results and discussion

3.1 Proximate analysis

Moisture content of fresh WH and RSW biomass was 91.0 and 82.0%, respectively, while that in sun-dried condition was 19.5 and 2.3%. The moisture content was used in determination of the volume of water required for constitution of the substrates in digesters.

Table 1 displays the proportions of crude protein, crude fiber, crude fat, ash and carbohydrates in sun-dried WH and RSW biomass corrected for moisture content. The two biomass had large proportion of carbohydrates and fiber of 54.4 and 67% for WH and RSW, respectively, that signified a high potential for biogas production with RSW having a higher potential than WH, e.g., Funda [13]. However, conversion efficiency biomass largely depends on the operation conditions of acidification and methanogenic processes [11].

Crude fat has the potential of high conversion to biogas because of the large number of C and H atoms in their

molecules, but with long retention times [18]. However, the less than 1% proportions of crude fat in both WH and RSW make its contribution insignificant. Ash content in the biomasses indicates the inert portion of the biomass. Water hyacinth had 16% greater proportion of non-biodegradable content compared to the ruminal slaughterhouse waste indicating a less potential for gas production. The WH had a smaller proportion of protein at 12.8% compared to 17.3% for RSW; however, the corresponding lesser proportion of carbohydrate and greater proportion of ash would reduce its impact on the carbon-to-nitrogen (C/N) ratio.

3.2 Crude fiber characteristics

The crude fiber components, which made up 15.6 and 18.4% of WH and RSW, respectively, were analyzed for lignin, cellulose, hemicellulose and ash. Water hyacinth had a smaller proportion of lignin of 9.9% compared to 25.5% for RSW suggesting WH may biodegrade faster than RSW (Fig. 3). The proportion of lignin was also less than the 25–36% range in common wood biomasses indicating that WH would be a better plant substrate for biogas production than terrestrial plants [5]. On the other hand, the proportion of lignin in RSW was at the lower end of

Table 1 Dry weight proportions of crude protein, fiber and fat, ash and carbohydrate in WH and RSW

Biomass	Parameter				
	Crude protein (%)	Crude fiber (%)	Crude fat (%)	Ash (%)	Carbohydrates (%)
Water hyacinth	12.8 ± 0.03	19.4 ± 0.27	0.91 ± 0.02	31.9 ± 0.40	35.0 ± 0.02
Slaughterhouse waste	17.3 ± 0.29	18.9 ± 0.18	0.48 ± 0.35	16.2 ± 0.13	47.1 ± 0.08

Fig. 3 Crude fiber by weight composition of lignin, cellulose, hemicelluloses and ash in WH and RSW

Table 2 Percentage elemental composition and carbon-to-nutrients ratios for WH and RSW

Biomass	Parameter					
	Carbon (C) (mg/L)	Nitrogen (N) (mg/L)	Potassium (K) (mg/L)	Phosphorus (P) (mg/L)	C/N ratio	c/p ratio
Water hyacinth	19,223 ± 350	2049 ± 60	170 ± 0.03	62 ± 7	9.38:1	310:1
Slaughterhouse waste	26,984 ± 600	1430 ± 260	7694 ± 19.65	41 ± 1	18.86:1	656:1

Table 3 Composition of total solids (TS), volatile solids (VS), total suspended solids (TSS), volatile suspended solids (VSS), total chemical oxygen demand (TCOD), soluble chemical oxygen demand (SCOD), and volatile fatty acids (VFA) and pH for WH and RSW

	Parameter							
	TS (g/Kg)	VS (g/Kg)	TSS (g/Kg)	VSS (g/Kg)	TCOD (g/L)	SCOD (g/L)	VFA (g/L)	pH
WH	187.6 ± 1.7	108.9 ± 8.4	0.9 ± 0.6	1.1 ± 0.15	1.3 ± 0.1	0.7 ± 0.1	24.54 ± 2.2	6.4 ± 0.1
RSW	2.44 ± 8.4	1.74 ± 3.6	1.47 ± 1.5	0.98 ± 2.8	3.04 ± 0.0	2.72 ± 9.2	2.8 ± 0.14	7.1 ± 0.09

the wood biomass range indicating resistance to the initial digestion stages of hydrolysis and acidogenesis. Holocellulose, which comprise of cellulose and hemicellulose, accounted for 56% of WH biomass which was comparable to 52% for RSW. The large content of holocellulose in the WH fiber signified potential for biogas production under anaerobic digestion process (e.g., [34]). Proportion of ash in WH exceeded that in RSW consistent with results of proximate analysis.

3.3 Elemental characteristics

Table 2 summarizes the elemental composition for WH and RSW. Water hyacinth had 29% less carbon than RSW, which was consistent with the lesser proportion of carbohydrates and greater proportion of ash observed in the proximate analysis. The observation indicates a lesser potential for biogas production for WH compared to RSW. The (C/N) ratios of 9.38 and 18.75 for WH and RSW, respectively, were at the lower and upper limits of the recommended range of 8–20 for optimal biogas production [17]. Depressed C/N ratio can cause ammonia inhibition while ammonia accumulation can result in pH values exceeding 8.5, which inhibit the action of methanogenic bacteria. On the other hand, C/N ratio can lead to N deficiency [25]. Co-digestion of the two substrates has potential for balancing the C/N ratio within the optimum range (e.g., [28]).

The observed potassium concentration of 137 mg/L in WH was below the optimal range of 200–400 mg/L [48] while the 7476 mg/L in RSW was in the inhibitory range. Mixing the two substrates has potential for balancing the potassium concentrations to the optimal range thereby stimulating biomethanation. The carbon-to-phosphorus (C/P) ratios of 310 and 656 for WH and RSW, respectively,

Table 4 VFA composition for WH and RSW

Biomass	Parameter				
	Butyric (g/L)	Propanoic (g/L)	Lauric (g/L)	Valeric (g/L)	Acetic (g/L)
RSW	24.1 ± 0.3	31.8 ± 1.8	31.4 ± 1.5	0.08 ± 0.003	30.3 ± 0.4
WH	16.2 ± 0.6	21.3 ± 1.1	21.1 ± 0.4	0.06 ± 0.002	21.0 ± 0.1

exceeded the optimum ratio for hydrolysis and acidogenesis stages of 100:1 and that for methanogenesis stage of 150:1 [35, 48] indicating phosphorous deficiency in both substrates.

3.4 Biochemical characteristics

Table 3 shows the mean biochemical characteristics for WH and RSW. The total solids (TS) for RSW and WH were 187.6 and 2.44 g/kg of samples of which 58 and 72%, respectively, were composed of organic matter (VS) while 43 and 16%, respectively, were fixed solids (FS) and ash. TCOD concentrations in RSW and WH were 3.04 g/L and 1.3 g/L, respectively, indicating high and low, respectively, content of organic matter in these substrates. Ruminal slaughterhouse waste samples had 56% VS, suggesting large amount of organic matter and microorganisms in the rumen contents substrate. The VFA properties for WH and RSW are presented in Table 4.

3.5 Biogas generation

Figure 4 shows cumulative biogas production for digestion of WH and RSW separately and in co-digestion at 32 °C over a period of 60 days. Biogas production for RSW

Fig. 4 Daily methane gas for WH, SHW and co-digested WH with RSW at 4:1 and 5:1 proportions at 32 °C

Fig. 5 Cumulative methane gas for WH, SHW and co-digested WH with RSW at 4:1 and 5:1 proportions at 32 °C

exhibited longer initial phase of up to 20 days, which associated reduced accessibility of the substrate by its large lignin component in the fiber (e.g., [31]). Thereafter, biogas production increase rapidly and remaining relatively uniform up to day 60 to achieve accumulative production

of 42 mL/kg biomass. On the other hand, WH which had a smaller proportion of lignin showed a uniform biogas production over the 60 days residence time. However, it achieved less than 50% of the RSW biogas production, which was attributed to less carbohydrates, depressed C/N ratio of 9.9 and below optimum C/K ratio. Co-digestion of WH with RSW at 1:4 and 1:5 RSW: WH ratio improved the startup rate above that for both biomass; The 1:4 RSW: WH ratio increased biogas production WH over 60 days residence time by 87% to achieve 90% of that for RSW (Fig. 5).

4 Conclusions

Fiber and proximate characteristics of water hyacinth indicated that it has significant concentrations of cellulose, hemicellulose and carbohydrates of 331,200, 231,800 and 447,800 mg/L, respectively, and lesser concentration of lignin of 99,400 mg/L that is desirable in biomass for biogas production. The C/N for WH of 9.4 was at the lower limit for optimal biogas production of 8 mg/L that demarcates potential ammonia toxicity while that for RSW of 18.8 was near the upper limit of 20 mg/L for nitrogen

deficiency. Therefore, co-digesting of WH with RSW has potential to balance of C/N ratios and other parameters for improved biogas production. Co-digestion of WH with RSW improved WH gas production demonstrating complementary effect of the two substrates. However, commercialization of the co-digestion would need to establish the optimal mix proportions and identity of microbial communities involved in the digestion process.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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