



Biogas yield assessment from the anaerobic co-digestion of food waste and *cymbopogon citratus*

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Abstract

This study, aimed at maximizing the biogas yield from the co-digestion of food waste (FW) and *cymbopogon citratus* (CC) was done in reactors (Rs) I–V at temperature of 36 ± 2 °C. Rs I, II, III, IV and V with respective FW: CC of 100:0; 80:20; 60:40; 40:60; 0:100 had mean biogas yield of 0.41 ± 0.02 , 0.68 ± 0.05 , 0.49 ± 0.02 , 0.29 ± 0.01 , and 0.22 ± 0.03 L/gVS, respectively. From the modeling result, while R I had the least latency (λ) of 3.9, RV had the highest value of 11.2 days. RII also had a reasonably low latency (λ) of 5.2 days. Top maximum specific biogas yield (R_m) of 0.48 L/gVS/day and maximum biogas production potential (A) of 19.9 L/gVS were obtained from RII. The high R^2 values of 0.99–0.89 obtained from the simulation analysis showed a good fit with the modified Gompertz model. The study has revealed that FW: CC of 80: 20% could be most appropriate for optimal biogas production.

Keywords Waste management · Renewable energy · Anaerobic digestion · Biogas · Optimization study

Introduction

The importance of energy in the growth and development of a country's economy cannot be overemphasized. Until recently, the world had majorly relied on fossil fuels for industrial, transportation, and domestic needs [1]. These are, however, non-renewable and their consumption leads to the disruption of the environment. The use of fossil fuels is also heavily linked to greenhouse gas emission such as carbon (IV) oxide [2]. Research has shown that current energy production matrix comprises 85% fossil fuels [3–5]. Furthermore, excessive and continuing use of fossil fuel has been predicted to cause energy crisis sooner or later. Its era is also speculated to end in about five decades to come due to non-renewability of sources [6–8]. Resolving these challenges requires the adoption of CO₂ neutral fuel systems [9].

These, coupled with unsteady price of crude and over dependence on oil import have led to prolific research into

renewable energy sources most especially, biogas production from anaerobic digestion [10]. In anaerobic digestion, an array of microorganisms breaks down organic substances to generate biogas (methane and carbon (IV) oxide). These microbes depending on their metabolic pathways could be hydrolytic, acidogenic, acetogenic, or methanogenic [11, 12]. In a developing country like Nigeria, bioenergy could serve as useful renewable energy alternative with little or no economic and environmental burdens. Studies have shown that mono-anaerobic digestion of many degradable substrates is easily inhibited as a result of poor C/N ratio, quick acidification of reactors due to the presence of long chain fatty acids etc. [13, 14]. This inhibition leads to poor biogas yield and sometimes complete process failure in the absence of external source of pH and nutrient [15]. Co-digestion, which is the anaerobic digestion of two or more substrates in a reactor at the same time has been proven to be a remedy to the challenges of mono-digestion [16]. The last few decades have witnessed a growing interest in anaerobic co-digestion studies. Literature has copious documentation of enhanced biogas yield arising from co-digestion of substrates. Examples are meat residues, vegetable and fruit waste [17]; kitchen waste, cow dung and water hyacinth [18]; food waste and maize husk waste [10] etc. This notwithstanding, optimal combination of the numerous available substrates for maximum biogas production is still an enormous challenge.

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As Nigeria is an agrarian nation, it has in abundance assorted biomass for biogas production. Examples are cymbopogon citratus (CC), food waste, agro-wastes, kitchen wastes etc. CC, though produced extensively in Nigeria due to its medicinal value is slowly biodegradable due to its high lignin and high nitrogen content [19]. However, co-digesting it with an appropriate substrate can enhance its biogas yield potential. *Cymbopogon citratus* (lemon grass) is an aromatic perennial plant of Grami-neae family, commonly found in temperate and tropical parts of the globe. Its maximum height at maturity is approximately 1 m. CC grows well on many soils and climates but better on properly drained fertile sandy loam soil with exposure to sunlight [19]. Though it is medicinally and industrially useful as a result of its citral content and important oil [20], many a time, after usage, it gets thrown away as waste in large quantity. Presently, not much has been reported about the reuse of *C. citratus* waste outside a few studies [19]. Indeed, scientific information on the anaerobic co-digestion of CC with food waste (FW) for biogas production is scanty or non-existent in the literature.

On the other hand, about 1.3×10^3 billion of FW is generated annually in the world. This implies that more than 30% of all food processed/produced for consumption usually ends up as waste on a global basis [21]. FW generation has also been predicted to increase globally by 44% in 2025 [22]. This huge quantity of FW is more worrisome in developing countries like Nigeria with no improved waste management systems. FW is easily biodegradable and has low nitrogen content. This makes its mono-digestion prone to acidification and system instability. Co-digesting with less biodegradable but high nitrogen content plant residue like CC can improve its biogas yield and reactor stability [18]. This study was, therefore, aimed at establishing the optimal percentage combination of FW and CC for maximization of biogas yield. Furthermore, the modified Gompertz model was used for the estimation of relevant bio-kinetic parameters for a deeper understanding of the performance of the reactors. The modified Gompertz model has been found most suitable for simulation of experimental data from anaerobic digestion of food waste [23, 24].

Methodology

Substrates collection and preparation

The *C. citratus* was obtained from gardens around some houses in Omu-Aran community, Kwara State and stored dry in a bucket for 40 days for the grasses to degrade. Using a local hammer mill, the grasses were crushed to about 2-in. size or less and stored in a clean air-tight container in the laboratory before the start of the anaerobic digestion experiments [10]. Food waste (FW) was collected from cafeteria

waste bins at Landmark University, Kwara State, Nigeria every day for five working days. In line with [10], bones and inorganic substances in the FW were removed almost immediately. Through the use of a small electric blender, the food waste was crushed and homogenized. The resulting substrate was stored in a freezer at 4 °C prior to the beginning of experiments.

Substrate characterization

Prior to mixing the FW and CC substrates for digestion, important chemical parameters of the substrates were determined. Following procedures in [25], the measurement of total solids (TS) and volatile solids (VS) were done three times with an oven (DHG-9053A, Controls, Italy). Methods in [25] were equally followed in the determination of substrates' $\text{NH}_4^+\text{-N}$, Na, Ca, Mg TKN, Cl, P, K, S with a photometer (Palintest Photometer, model 7100 England). Measurement of carbon content also followed standard methods [25]. Measurement of pH of the FW and CC substrates was done with pH meter (PHS-3C, SEARCH TECH, UK). The obtained chemical parameters and their values are presented in Table 1.

Batch anaerobic digestion

Batch anaerobic digestion experiment was done in five (5) similar computer-controlled 10 L reactors with five (5 L) working volume (model PDANC, EDIBON, Spain). The reactors were tagged I, II, III, IV, and V. Prior to putting the substrates into the reactors, VS of the feeding substrates was determined. In line with the split plot approach, five (5) treatments of various mixture of FW and CC were utilized

Table 1 Chemical properties of the substrates

Parameter	FW	CC
TS (%)	24.3±0.1	9.3±0.9
VS (%)	15.2±0.9	7.9±0.6
$\text{NH}_4^+\text{-N}$ (%)	1.4±0.3	2.7±0.1
TKN (%)	11.5±0.3	16.1±0.3
Cl (%)	1.7±0.1	6.8±0.7
P (%)	3.1±0.2	3.2±0.2
Ca (%)	2.9±0.1	10.2±0.4
Mg (%)	1.9±0.3	1.7±0.2
K (%)	3.2±0.2	1.9±0.2
S (%)	3.8±0.1	5.3±0.8
Na (%)	3.1±0.4	3.1±0.6
pH	4.2±0.3	6.5±1.1
C/N ratio	28.8±2.5	12.6±0.6

Measurement was on wet basis; results are indicated as average ± standard deviation ($n=3$)

for the experiment (Table 2). The reactors were set up and ran following the manufacturer's (EDIBON, Spain) instruction manual. The initial TS of substrates in the reactors was 8% [26].

The experiments ran mesophilically at 36 ± 2 °C and stopped after 40 days when no reasonable biogas yield was obtained again. In line with the procedure in [27], daily biogas yield was obtained by water displacement approach through the reactors' volumetric tanks graduated in millimeter. As stipulated in the EDIBON manual, actual volume of biogas yield was gotten by a conversion factor of 0.01628 L per millimeter.

In accordance with [27], the displaced water was first acidified to pH 3 to prevent the dissolution of CO₂ into water. Digestion temperature and pH were regularly measured online with inbuilt sensors. The experiments were ran twice and average values of daily biogas yield recorded. With a gas chromatograph (GC), model GC122, BUCK, China, equipped with a Stabilwax-DA column (3 m × 0.32 m × 0.5 μm) and flame ionization detector, biogas methane content was analyzed two times every week. The carrier gas (nitrogen) was set at 5.2 mL/min. While the column

temperature was set at 40 °C, the detector temperature was kept at 200 °C. The experiment and analyses were all carried out in the Environmental Engineering Laboratory of Landmark University. The picture of the reactor is shown in Fig. 1.

Modified Gompertz modelling

Equation (1) shows the modified Gompertz model used by lots of researchers for estimation of relevant anaerobic digestion bio-kinetics [24].

$$A_t = A \exp \left\{ - \exp \left[\frac{R_m \times e}{A} (\lambda - t) + 1 \right] \right\} \quad (1)$$

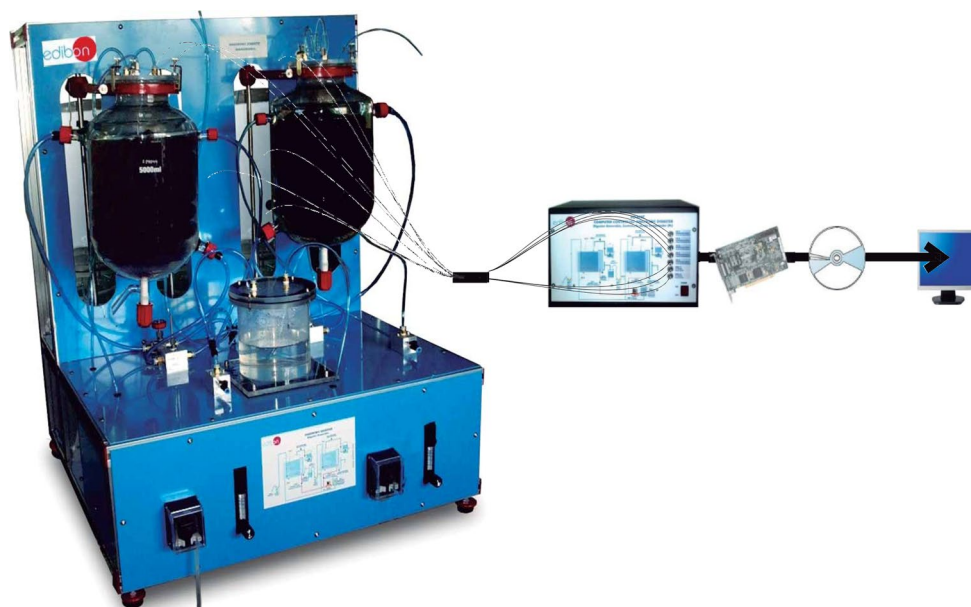
where in A (L/gVS) = maximum biogas yield potential; R_m (L/gVS/day) = maximum specific biogas yield; λ (days) = latency (days) = time of biogas yield; A_t (L/gVS) = cumulative biogas production. Equation (1) was solved using solver optimization tools in Microsoft Excel (2010 version). Adopting a 5% significant level, a two-way

Table 2 Influent substrate properties

Parameters	RI	RII	RIII	RIV	RV
FW: CC (%) (w/w) based on total weight (g)	100:0	80:20	60:40	40:60	0:100
Total weight of sample (g)	45	45	45	45	45
VS (g/L)	4.2	3.9	3.8	4.1	3.5
C/N ratio	28.8 ± 2.5	23.5 ± 1.2	20.6 ± 0.8	19.2 ± 1.1	12.6 ± 0.6
pH	6.8	7.1	7.2	6.9	6.0

Measurement was on wet basis; food waste (FW); *Cymbopogon citratus* (CC)

Fig. 1 Picture of the computer-controlled anaerobic digester (PDANC model) utilized for the experiment



analysis of variance (ANOVA) was applied to statistically interpret yields from each of the reactors.

Results and discussion

Characterization of substrates

The characteristics of individual FW and CC and the various mixtures are shown in Tables 1 and 2, respectively. While the concentration of total solids (TS) was 24.3% for FW, it was 9.3% for CC. FW and CC also had a volatile solid concentration of 15.2% and 7.9%, respectively. The high TS and VS concentrations of FW indicate that microbes were abundantly available in the FW sample [28, 29]. Generally, CC contains carbohydrates, lignin and hemicellulose, whereas FW contains a sufficient amount of anaerobic bacteria, and a wide range of important nutrients for maximum microbial growth. RI in the first 16 days of digestion had pH close to 6.2. It, however, reduced as digestion progressed to about 5.4 signifying signs of acidification. The mean digestion pH in Rs I–V ranged from 6.0 to 7.2 (Table 2) which is conducive for the activities of anaerobic bacteria [10]. Table 1 shows that the value of $\text{NH}_4^+\text{-N}$ was greater in CC. $\text{NH}_4^+\text{-N}$ enhances process equilibrium during anaerobic digestion. Recently, [28] reported higher ammoniacal nitrogen content in cattle manure (CM) than in palm oil mill

effluent (POME) and concluded that the higher ammonia from the CM enhanced system stability during the anaerobic co-digestion of CM and POME for biogas production. In a study on the anaerobic digestion of fruit, vegetable, and yard wastes by [30], pH and $\text{NH}_4^+\text{-N}$ were, respectively, found to increase from 6.9 to 7.3 and 765–955 mg/L. From Table 2, Rs I–V had C/N ratio of 28.8 ± 2.5 , 23.5 ± 1.2 , 20.6 ± 0.8 , 19.2 ± 1.1 and 12.6 ± 0.6 , respectively. For optimum biogas production, anaerobic microorganisms require balanced proportion of carbon for energy and nitrogen for protein. Studies have shown that one of the ways to enhance biogas production from substrates is to keep C:N ratio within the neighborhood of 25–35 [30, 31]. While very high C:N ratio (excess carbon) slows down anaerobic digestion, very low C:N ratio (excess nitrogen) limits biogas yield and makes the entire process end up with a stinky pile. Bardi and Rad [31] have also reported that nitrogen deficiency in a substrate limits microbial activity. Generally, results obtained from this study as displayed in Fig. 2 shows that reactors with C/N ratios between 20 and 30 achieved better yield than those outside the range.

Biogas production performance of the reactors

Mean biogas yield of 0.50 ± 0.04 , 0.71 ± 0.07 , 0.54 ± 0.05 , 0.30 ± 0.03 , and 0.24 ± 0.02 L/gVS was, respectively, produced in Rs I–V. RII, followed by RIII, had the highest

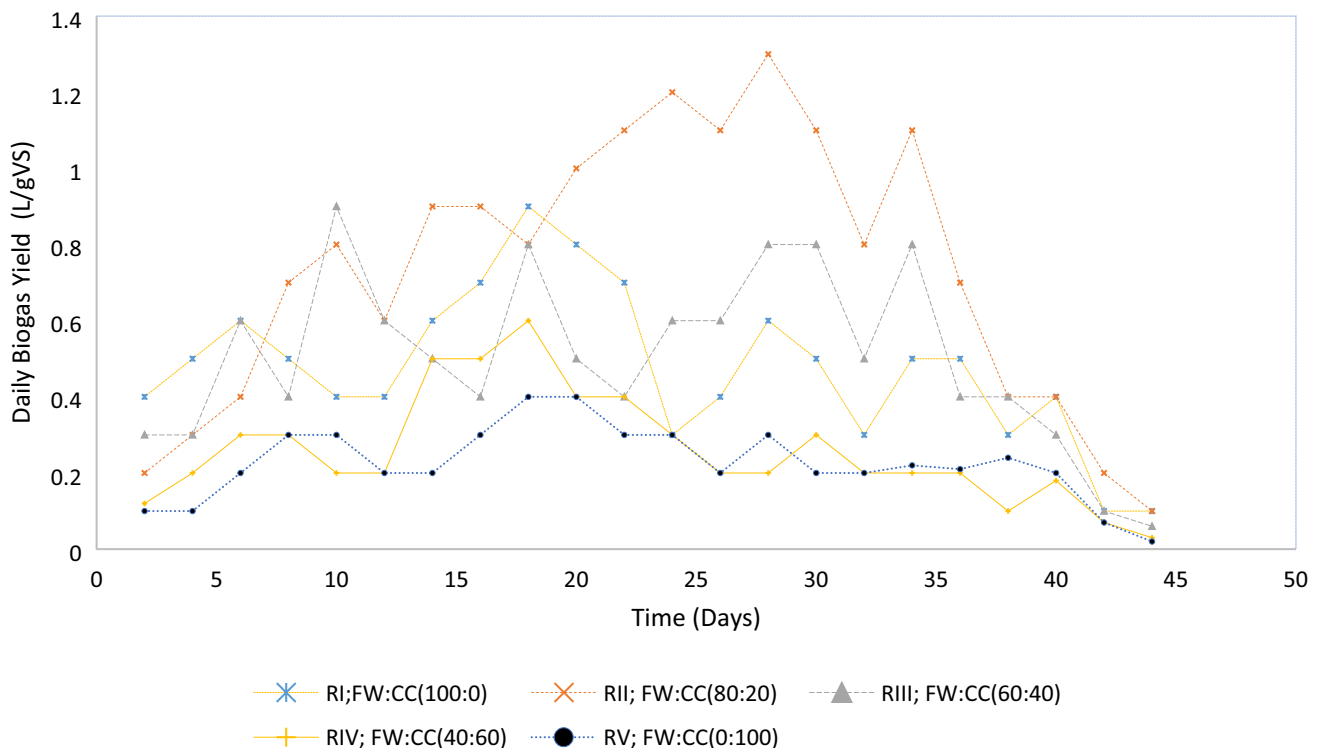


Fig. 2 Daily biogas yield for RI–RV

biogas yield (Fig. 2). The observed poorest performance from RV with 100% CC could be attributed to the low C/N ratio against the prescribed range of 20–35 [10, 29] and higher lignin content [26]. According to [30], low ratio of C/N causes acidification and, therefore, inhibits methanogenesis. Lignin has also been reported to inhibit initial hydrolysis in anaerobic digestion [26]. As shown in Fig. 3, total biogas yield for Rs I, II, III, IV and V was, respectively, 10.39, 12.64, 11.84, 5.65, and 5.23 L/gVS. ANOVA at $p < 0.05$ for the five reactors (Table 3) indicates a significant difference in the biogas yield across the reactors. Rs IV and V were noted to have similar low biogas yield. This could be linked to having the largest quantities of CC. The low yield in RIV implies that though CC can improve biogas yield when co-digested with FW, excessive amount of CC relative to FW can cause inhibition. This corroborates the finding of [26] for the co-digestion of cow dung, water hyacinth, and waste paper in which optimal yield decreased with increase in paper quantity beyond the optimal mix ratio. The authors attributed the decrease to decreased hydrolysis with

increased quantity of wastepaper. In line with [32], over 70% of the cumulative biogas yield occurred in the first 18 days of digestion. Maragkaki et al. [33] in their study on biogas production from co-digestion of sewage sludge (SS), FW, cheese whey (CW) and olive mill wastewater (OMW) found that co-digesting 3% of food, cheese and olive mill wastewater (FCO) with sludge increased daily biogas yield from 437 ± 132 to 533 ± 160 mL/L_{reactor}/day.

Other than RII with peak biogas yield of 1.21 L/gVS on the 26th day, the peak yield of Rs I, III, IV, and V of 0.78, 0.72, 0.49 and 0.33 L/gVS, respectively, occurred between the 19th and 22nd day. Performance of RII could be linked to the synergy of microorganisms due to the availability of some limited amount of CC and the resultant C/N ratio of 23.5 ± 1.2 [16–20]. When FW and pretreated yard waste were anaerobically digested at the F/M ratio of 2.0, two biogas yield peaks were observed on the 7th day and 20th day [32]. While the peak of the 7th day was attributed to high sCOD content (3780 ± 180 mg/L) and fast degradation to methane, the peak that occurred on the 20th day was attributed to

Fig. 3 Cumulative Biogas yield for RI–RV

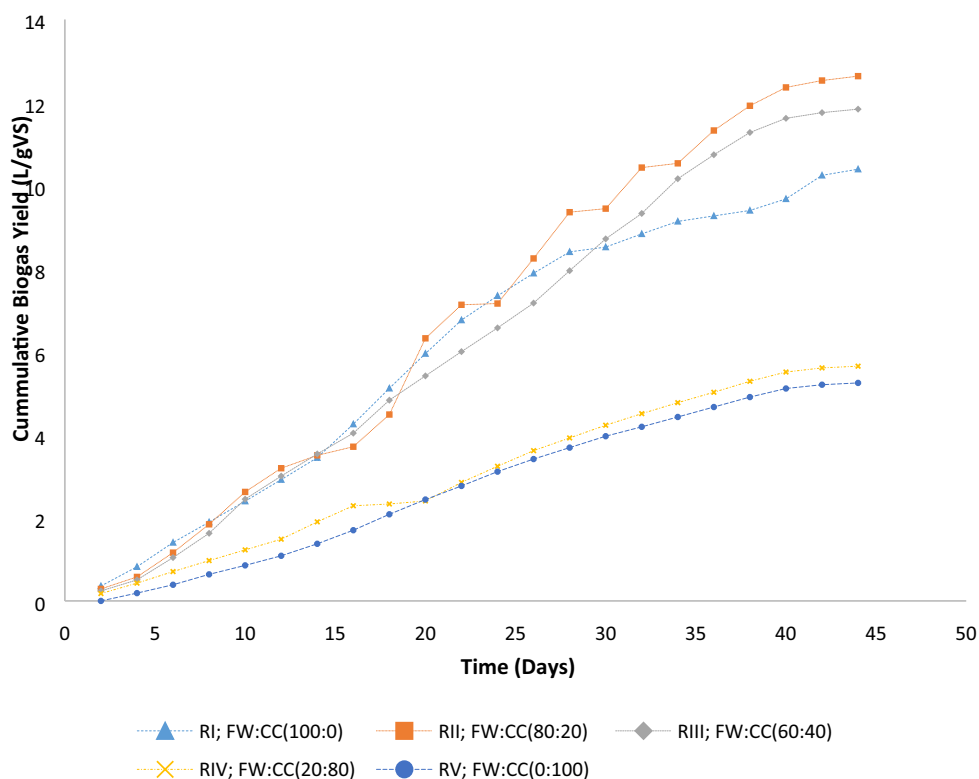


Table 3 Two-way ANOVA with no replication

Source of Variation	SS	df	MS	F	p value	F crit
Rows (yields across the reactors)	3.41	21	0.22	7.62	4.43E-08	2.83
Columns (yield from each reactor)	4.24	3	1.05	62.78	8.27E-17	3.86
Error	0.83	63	0.83			
Total	7.65	87				

macromolecules degradation and crude protein [32]. The mean methane content of biogas from the various reactors is shown in Fig. 4. RII was again found to have cleaner biogas with respect to methane content showing that co-digestion of FW and CC for bioenergy is best at 80% FW and 20% CC. This can, therefore, be a way of treating the respective wastes with additional huge benefit of bioenergy generation. In a recent study in which food waste was co-digested with

sewage sludge, biogas with methane content of 71%, 68%, 68%, 66%, 67%, 67%, and 59% were, respectively, obtained in Reactors 1–7 used for the experiment.

Output from modified Gompertz modelling

Plots arising from the modified Gompertz modelling are shown in Fig. 5. Result from the modelling (Table 4) reveals that excessive increase in the quantity of CC increased latency. Latency (λ) is described as the least time needed for initiation of effective methanogenesis in a reactor. The minimum values of λ were obtained as 3.9 days for RI and 4.6 days for RII. These two reactors contained the lowest quantity of CC substrate. A good R^2 range of 0.89–0.99 was obtained (Table 4) and indicates good fit. FW contains large quantity of highly degradable matter and indigenous bacteria and hence starts generating biogas not long after the commencement of digestion [23]. This notwithstanding, because of its high C/N ratio, it often undergoes acidification due to excessive production of intermediate products like volatile fatty acids [34]. The intermediate product inhibit further biogas yield as anaerobic digestion progresses making it essential to co-digest FW with agro-waste matters like CC for C/N adjustment [34].

Table 4 reveals that 20% CC addition led to increase in the maximum specific biogas production (R_m). Subsequent addition of CC to become 40% and 60% of the substrate reduced R_m . While RI with only FW had R_m of

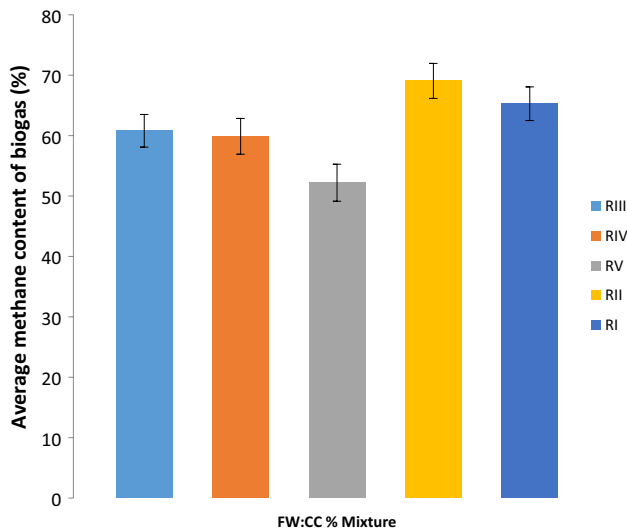


Fig. 4 Mean methane content of biogas yield

Fig. 5 Plot of modified Gompertz modelling for RI–RV

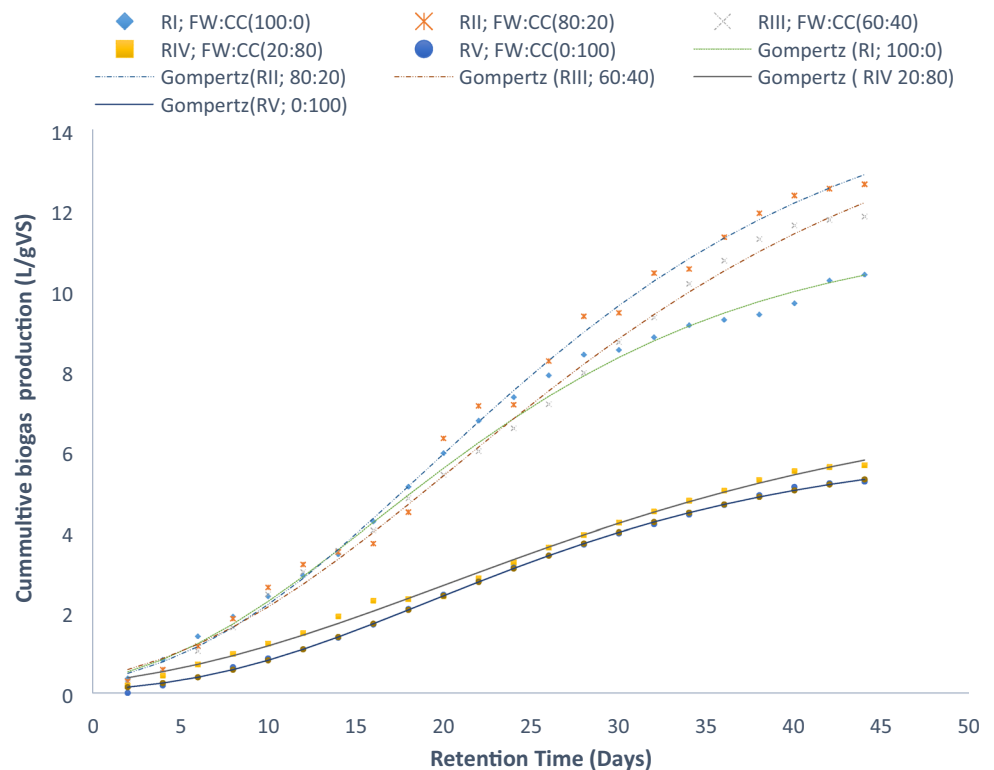


Table 4 Estimated parameters from the modified Gompertz model

Reactor	FW:CC mix ratio	A (L/gVS)	R_m (L/g VS/day)	λ (days)	R^2
RI	100:0	10.53	0.41	3.9	0.99
RII	80:20	19.62	0.49	4.6	0.97
RIII	60:20	14.38	0.32	5.8	0.94
RIV	40:60	7.51	0.28	6.2	0.91
RV	0:100	6.43	0.19	9.4	0.89

0.41 L/gVS/day, R II had R_m of 0.49 L/gVS/day. Additional increase in CC quantity as found in RIII, IV and V reduced R_m indicating that for profitable running of large plants, the optimal combination of FW and CC should, respectively, be within the neighborhood of 80% and 20%. Since R_m relates to the quantity of methanogens present in a reactor and their activities, RII could be said to have had a better activity of methanogens and thus improved biogas yield [21]. Deepanraj et al. [23] obtained R_m of 712.6 mL/day using the modified Gompertz model to describe experimental data from the anaerobic digestion of untreated food waste. This is higher than the value of 0.41 L/gVS/day obtained in this study and could be attributed to the difference in the composition of food waste digested in both studies.

Table 4 also shows that R I with only FW had a maximum biogas production potential (A) of 10.53 L/gVS. However, a reasonable improvement to 19.62 L/gVS was gotten in RII with 20% CC. When the quantity of CC went up to 50%, the value of A (L/gVS) started to decrease. The reduction in value of A (L/gVS) in RIV was 45.3%, while the improvement in A (L/gVS) gotten in RII, and III was 59.2% and 19.2%, respectively, in relation to RI. The increase in biogas yield in RII indicates that a different metabolic pathway must have occurred with better degradation as a result of the adjustment in substrate characteristics, brought about by the addition of limited amount of CC [24]. The reduction in Rs III and IV could be because agro-waste materials have large amount of lignin which makes hydrolysis a limiting reaction pathway [21]. Panigrahi et al. [32] in a recent study on co-digestion of food waste with pretreated yard waste applied three different models for the simulation of the experimental data obtained. The study reported that the smallest difference between experimental and predicted methane yield was observed with the modified Gompertz model (3.7–15.4%). Yoon et al. [24] also used the first-order kinetic model and modified Gompertz model to describe the co-digestion of wastewater sludge and food waste. Result obtained showed a higher correlation value ranging from 0.92 to 0.99 for the modified Gompertz model [24].

Conclusion

The study evaluated the optimal combination of *C. citra-tus* (CC) and food waste (FW) for enhanced biogas yield. Maximum mean biogas production of 0.69 ± 0.05 L/gVS was gotten in RII. The modelling result showed that the highest A and R_m values were also gotten in RII with 80% FW and 20% CC. The study further revealed that when CC was increased to above 20%, A and R_m decreased while λ increased indicating inhibition/reactor failure as noted in Rs IV and V. The research concludes that the co-digestion of 80% FW and 20% CC could be suitable for optimum production of biogas on industrial scale.

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