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Research article

Rice straw co-digestion potential with cow dung and poultry droppings for maximizing biogas production in Bangladesh

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ABSTRACT

Rice is the staple food of the people of Bangladesh. Burning and landfilling of carbon-rich rice straw (RS) causes greenhouse gas emissions. On the other hand, cow dung (CD) and poultry droppings (PD) produced from the livestock sector in Bangladesh could be a potential threat to the environment if the wastes are not properly managed. However, anaerobic co-digestion of RS with CD and PD could be an effective means of biogas generation. Therefore, co-digestion of CD and PD with carbon-rich RS was conducted in batch assay at seven different mixing ratios (100:0, 90:10, 70:30, 50:50, 30:70, 10:90, 0:100) separately. Mesophilic condition (35 °C) was maintained for 92 days of digestion time to investigate biogas production potential and find out optimal mixing ratios of both co-digestion sets. Co-digestion of CD and RS at 70:30 ratio significantly showed maximum biogas yield (441.7 ± 54.1 ml/gVS). Additionally, an increase in biogas yield in this ratio was 212.11 % and 38.10 % compared to mono-digestion of CD and RS, respectively. Another co-digestion set of PD with RS showed highest biogas yield (344.8 ± 22.3 ml/gVS) at 90:10 ratio. The 90:10 ratio of PD and RS improved biogas yield by 173.16 % and 7.8 % as compared to mono-digestion of PD and RS, respectively. Co-digestion of RS with CD and PD had a statistically significant effect ($P \leq 0.05$) on biogas production. Furthermore, kinetic modelling outcomes suggested the modified Gompertz model as ideal for forecasting biomethane production over time in both cases. The findings of this study will help in the implementation of ACoD at the field level.

1. Introduction

Energy is a crucial input for improving quality of life, but sustainable energy production is still an issue in Bangladesh. In Bangladesh, the electricity production capacity from natural gas is 51.05 %, and the renewable energy share is only 2.04 % [1]. Transitioning from fossil fuel to cleaner and sustainable energy is one of the major challenges in ensuring energy security in Bangladesh as well as in the world. In line with Sustainable Development Goal, 7 (affordable and clean energy) set by the United Nations, the Government of Bangladesh has set a plan to generate 20 % of total electricity from renewable sources like solar, wind, biomass, etc. by 2030 [2]. One of the avenues that has been under scrutiny is the transformation of biogenic residues, from animal farming, agricultural activities, and municipalities to energy, which are not being utilized to their maximum potential. By better utilization or reuse of biogenic residues, Bangladesh can contribute towards clean energy and circular food systems initiatives. National Renewable Energy

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Policy 2008 also describes the use of biomass for energy production using different waste-to-energy conversion technologies [3].

Bangladesh produces considerable amounts of biogenic residues from crop and livestock sectors. The livestock population in developing countries like Bangladesh is currently reported to be 304.1 million poultry and 24.5 million cattle [4]. Each year around 2.1 million tons of poultry droppings and 12.3 million tons of net available cow dung [5] are produced in Bangladesh. Raw manure dumping causes eutrophication, emission of toxic gases, contamination of soil and air, malodorous air emission, and lack of proper use of nutrient content of manure [6]. Around 14.5 % of anthropogenic greenhouse gas is emitted from livestock farming [7] due to improper waste management. On the other hand, the staple food of Bangladesh is rice where the production of RS is 29.5 million tons [5]. Common methods of rice straw disposal include open burning causes greenhouse gas emissions [8–10] and plowing straw back into the fields might result in foliar diseases which results in lower crop production [10]. However, RS is also used as animal feed, fertilizer, and leftover for natural degradation or burning as a result, different oxides of carbon, sulfur, and nitrogen are produced, which cause hazards for humans and animals [11]. AD can be a solution to these waste management problems and energy production from livestock and crop residues as it reduces greenhouse gas emissions and produces bioenergy as biogas [6,12,13]. However, mono-digestion of CD and PD is mostly practiced in Bangladesh [14]. Lower biogas production from AD of livestock manure was observed [5,6,15–17], which might be due to nutrient imbalance during manure digestion resulting in partial breakdown of organic matter [18]. On the other hand, anaerobic digestion could also be an option for producing biogas from RS [11,18]. However, bio-methanation of RS also does not result in optimal yield due to the recalcitrant structure of RS and poor nitrogen content [20–22].

Recent studies suggested ACoD of different biomass over mono-digestion [23,24] due to its different benefits like dilution of toxic substances, proper nutrient balance, and synergistic effects on microorganisms. Thus, co-digestion of CD and PD with carbon-rich lignocellulosic co-substrates such as RS may maximize methane yield by accelerating substrate depolymerization, degradation, and solving management problems of various waste at the same time. Recent studies summarized ACoD of livestock waste with lignocellulosic waste [18,25] and carbon-rich fruits and vegetable waste [13,18,26,27] to improve biogas yield. A recent review of the literature showed that biogas production potential from anaerobic co-digestion of rice straw with cow dung [9,28], pig manure [29], and swine manure [30] were assessed, but did not identify any mixing ratio for maximum gas production. Physical and chemical characteristics of substrates (pH and C/N ratio) largely affect microbial reactions during biogas production [31]. Characteristics of CD and PD can be varied due to their feed and input characteristics [32]. So, a complete investigation of substrate characteristics may help to select the feed rate of different substrates for nutrient balancing during co-digestion. To the best of our knowledge, there is no complete investigation to find out the appropriate ratio of co-digestion of CD and PD with RS in Bangladesh for which biogas production can be maximized and recommended for use commercially. Finding the optimal ratio and characterization of substrates will not only improve biogas yield but also may help to properly manage waste and develop a proper structure of biogas plant concerning the requirement of feeding amount and reactor design. However, the impacts of mixing substrates on biogas yield and examining the AD process using mathematical modelling are largely missing and thus to control process parameters for increasing biogas yield. Therefore, this study aimed to investigate biogas and methane yield of two co-digestion sets (CD with RS and PD with RS), characterization of feedstock, and find out optimal mixing ration for maximum biogas production for managing several wastes at a time and to commercialize anaerobic co-digestion technology with higher efficacy.

2. Materials and method

2.1. Substrates and inoculum

The batch assay was carried out at the biogas laboratory in the GEKH (Green Energy Knowledge Hub), of the Department of Farm Power and Machinery, Bangladesh Agricultural University (BAU), Mymensingh, Bangladesh. Cow dung and poultry droppings used for the experiment were collected from Dairy Farm and Poultry Farm, Bangladesh Agricultural University (BAU), Mymensingh, Bangladesh, respectively. Rice straw (RS), which was used as an agricultural by-product collected from the agronomy field of BAU, Mymensingh and chopped following Muhayodin et al. [33] into small pieces using scissors to accelerate the AD process. Bio-slurry of cow dung from Continuous Stirred Tank Reactors (CSTR) of the GEKH lab was used as inoculum. Inoculum was kept in an incubator for 15 days in mesophilic condition (35 °C) as Khatun et al. [13] recommended storing inoculum in such condition helps to produce potential biogas which will reduce biogas generation during the digestion period.

2.2. Analytical methods

Physical and chemical properties of substrates such as pH, Total Solid (TS), Volatile Solid (VS), Total Nitrogen (TN), Total Ammonium Nitrogen (TAN), and C: N ratio for different mixing ratios were examined. Standard procedure [34] was followed to measure TS and VS. The pH meter (MW 150 Milwaukee pH meter) was used to measure the pH value of substrates. TN content of the substrate was determined by micro-Kjeldahl method [35]. TAN was measured using photometric kits (Spectroquant kit, Merk, USA) and photometer. The C/N ratio was calculated following equation (1) [36].

$$\frac{C}{N}=\frac{VS\%}{1.76\times TN\%} \tag{1}$$

Three replications of each test group were examined and average of these replications was considered for further analysis.

2.3. Experimental setup

The experiment was carried out in a batch assay system, as stated by Rahman et al. [18]. There were two sets of experiments: One set was CM with RS and another was PD with RS. For each set, seven mixing combinations (100:0, 90:10, 70:30, 50:50, 30:70, 10:90, and 0:100) were used to determine the optimal mixing ratio for maximum methane production. In this experiment, 500 ml air-tight batch bottles with butyl rubber stoppers were used as digesters. Each batch bottle was filled with 250 g of inoculum and the required amount of substrate was added to maintain 1:1 VS ratio following some previous batch studies [13,18,24]. Using Eq. (2) [18], quantity of substrate for seven mixtures were determined on the basis of VS.

$$\mathrm{Pi} = \frac{Mi \times Ci}{Ms \times Cs} \tag{2}$$

Where P_i is mass ratio which is equal to 1, M_i is mass of inoculum in g, C_i is % VS of inoculum, M_s is mass of substrates in g, C_s is % VS of substrate.

All test group were triplicated to determine the biogas production. The batch bottles were incubated for 92 days to get maximum producible biogas from substrates in an incubator (ICP 110; Merk, Germany). Mesophilic temperature condition (35 ± 1 °C) was used in the experiment. Anaerobic condition was ensured by flushing the headspace of all the batch bottles for 2–3 min with nitrogen gas. Routinely, the entire biogas was measured and biogas composition were analysed using a gas analyser (Optima 7 Biogas MRU Instruments, Inc, USA). Methane (CH_4) production from only inoculum was also observed and CH_4 produced from inoculum was subtracted from each sample to get methane yield from sample substrates only. Using Eq. (3) [34] methane yield was calculated.

$$BMP_{observed} = \frac{V_{(ino+biomass)} - V_{ino}}{mVS_{biomass}} \tag{3}$$

Where, $\mathrm{BMP_{observed}}$ is the observed biochemical CH_4 potential in ml/gVS, $\mathrm{V}_{\mathrm{(ino+feedstock)}}$ is the volume of CH_4 produced by feedstock mixed with inoculum in ml, $\mathrm{V_{ino}}$ is the volume of CH_4 produced by inoculum in ml, and $\mathrm{mVS_{feedstock}}$ is the mass of volatile solid in feedstock in gVS.

2.4. Biogas composition during ACoD

Biogas is composed of methane and carbon-dioxide (CO_2), which are the main components, but some other trace gases are also present in biogas in a small amount. Correction in CH_4 and CO_2 indicates the maximum possible CH_4 and CO_2 percentage in biogas neglecting all other components during ACoD. CH_4 and CO_2 percentages were corrected following equations (4) and (5) [13], respectively.

$$\%\mathrm{Corrected}\ CH_4 = \frac{\%Methane}{\%Methane + \%\ Carbon\ dioxide} \times 100 \tag{4}$$

$$\%\ \mathrm{Corrected}\ CO_2 = \frac{\%\ Carbon\ dioxide}{\%Methane + \%\ Carbon\ dioxide} \times 100 \tag{5}$$

Where,

%Methane = Methane content in biogas (%)

% Carbon dioxide = Carbon dioxide content in biogas (%)

2.5. Statistical analysis

All the data were analysed in Microsoft Excel 2016. Statistical analysis i.e., ANOVA (Analysis of Variance) was done to determine significant variation in gas production between different mixing combinations.

2.6. Effect of synergy

ACoD of two or more biomass exhibits variation in biogas production compared to AD of a single biomass which can be evaluated by synergistic effect [37]. The estimation of CH_4 production for different mixing ratios of substrates and the effect of synergy can be evaluated using equations (6) and (7) [38].

$$\mathrm{B_{Estimated\ (t)}} = \mathrm{B_{Measured-P\ (t)}} \times \mathrm{X} + \mathrm{B_{Measured-Q\ (t)}} \times \mathrm{Y} \tag{6}$$

Where, $\mathrm{B_{Estimated(t)}}$ is estimated CH_4 production at time t (ml/gVS), $\mathrm{B_{Measured\text{-}P(t)}}$ is measured CH_4 production of one substrate (P) at time t (ml/gVS), $\mathrm{B_{Measured\text{-}Q\ (t)}}$ is measured CH_4 production of another substrate (Q) at time t (ml/g VS), X is percentage of P and Y is percentage of Q.

$$\mathrm{Synergistic\ effect} = \frac{B_{Measured}}{B_{Estimated}} \times 100 \tag{7}$$

2.7. Kinetic analysis

The biodegradability rate of substrates and methane yield at a specific time may be predicted by using kinetic model [38]. Kinetics of the ACoD process were examined using three models as Cone model, modified Gompertz model, and Logistic model. The following equation used for Cone model (8) [13], modified Gompertz model (9) [39], and Logistic model (10) [40].

$$B(t) = \frac{B_o}{1 + (Kt)^{-n}} \tag{8}$$

$$B(t) = B_o \exp\left\{ - exp\left[\frac{R \times e}{B_o}(\lambda - t) + 1\right]\right\} \tag{9}$$

$$B(t) = \frac{B_o}{1 + \exp\left[4R\frac{(\lambda - t)}{B_o} + 2\right]} \tag{10}$$

Where, B(t) is CH_4 production at a given time t (d) (ml/gVS), B_o is highest CH_4 production potential of the substrate (ml/gVS), k is rate of hydrolysis (d^{-1}), the value of e is 2.7183, R is highest specific CH_4 production per day (ml/(gVSd)), λ is lag phase (d) and n is shape factor. MATLAB (R2018a) software was used for kinetics modelling.

Table 1
Physical and chemical properties of feedstock during ACoD.

Characteristics of Raw substrates							
		pH	TS (%)	VS (wb) (%)	TAN (g/l)	TN (%)	C:N ratio
CD		8.51 ± 0.02	14.63 ± 0.37	11.99 ± 0.32	4.15 ± 0	1.49	32.15 ± 0.03
PD		7.58 ± 0.08	27.15 ± 0.81	15.18 ± 0.51	0.9 ± 0	2.24	14.45 ± 0.07
RS		7.68 ± 0.04	71.74 ± 0.26	59.12 ± 0.07	0.675 ± 0.71	0.73	64.15 ± 0.15
Inoculum		7.27 ± 0	5.17 ± 0.25	3.63 ± 0.18	1.925 ± 4.95	1.23	32.5 ± 0.07
Characteristics of substrates with inoculum at different mixing ratio							
Mixing ratio		pH	TS (%)	VS (wb) (%)	TAN (g/l)	TN (%)	C:N ratio
CD:RS	100:0	7.4 ± 0.03	9.07 ± 0.16	6.75 ± 0.30	2.75 ± 1.41	1.29	32.76 ± 0.94
	90:10	7.67 ± 0	8.92 ± 0.28	6.85 ± 0.28	2.05 ± 1.41	1.68	25.96 ± 0.23
	70:30	7.58 ± 0.01	10.18 ± 0.45	7.86 ± 0.31	2.1 ± 2.83	1.15	38.18 ± 0.36
	50:50	7.44 ± 0.01	10.09 ± 0.13	7.77 ± 0.10	1.825 ± 0.71	1.04	42.28 ± 0.44
	30:70	7.42 ± 0	8.02 ± 0.34	5.7 ± 0.31	2.025 ± 0.71	1.26	32.03 ± 0.46
	10:90	7.47 ± 0.06	8.94 ± 0.16	6.75 ± 0.34	1.975 ± 0.71	1.26	34.06 ± 1.14
	0:100	7.4 ± 0.01	7.91 ± 0.24	5.84 ± 0.15	2.175 ± 0.71	1.21	34.80 ± 0.53
PD:RS	100:0	7.4 ± 0.05	9.93 ± 0.05	5.76 ± 0.20	1.55 ± 1.41	1.54	21.38 ± 0.66
	90:10	7.32 ± 0.04	9.03 ± 0.30	7 ± 0.26	2.925 ± 0.71	1.32	33.49 ± 0.66
	70:30	7.28 ± 0.01	9.18 ± 0.09	7.19 ± 0.18	2.35 ± 0	1.88	23.72 ± 0.62
	50:50	7.30 ± 0.4	8.09 ± 0.29	5.68 ± 0.29	2.025 ± 0.71	1.4	28.49 ± 0.44
	30:70	7.39 ± 0.03	8.95 ± 0.01	6.57 ± 0.28	2.175 ± 0.71	1.43	29.27 ± 1.21
	10:90	7.38 ± 0.11	9.04 ± 0.16	6.91 ± 0.12	1.8 ± 1.41	1.07	41 ± 0.75
	0:100	7.4 ± 0.01	7.91 ± 0.24	5.84 ± 0.15	2.175 ± 0.71	1.21	34.8 ± 0.53
Characteristics of digestate							
Mixing ratio		pH	TS (%)	VS (wb) (%)	TAN (g/l)	TN (%)	C:N ratio
CD:RS	100:0	6.92 ± 0	7.22 ± 0.48	5.42 ± 0.47	2.13 ± 0.71	1.71	24.96 ± 0.81
	90:10	7.49 ± 0.12	6.48 ± 0.25	4.66 ± 0.17	2.08 ± 0.71	1.46	28.09 ± 0.10
	70:30	7.4 ± 0.03	6.97 ± 0.28	4.88 ± 0.21	2.25 ± 1.41	1.68	23.69 ± 0.05
	50:50	7.4 ± 0.13	6.4 ± 0.13	4.69 ± 0.06	2.23 ± 2.12	1.57	26.74 ± 0.61
	30:70	7.57 ± 0.11	5.83 ± 0.13	4.32 ± 0.09	2.35 ± 2.83	1.49	28.36 ± 0.36
	10:90	7.54 ± 0.04	6.39 ± 0.27	4.26 ± 0.34	2.18 ± 0.71	1.74	21.79 ± 0.90
	0:100	7.60 ± 0.11	6.93 ± 0.15	4.74 ± 0.12	2.38 ± 0.71	1.54	25.2 ± 0.16
PD:RS	100:0	7.80 ± 0	5.91 ± 0.04	3.53 ± 0.02	4.05 ± 1.41	2.35	14.44 ± 0.05
	90:10	7.74 ± 0.04	5.87 ± 0.11	3.62 ± 0.06	3.35 ± 1.41	2.13	16.43 ± 0.18
	70:30	7.58 ± 0.08	5.86 ± 0.12	3.78 ± 0.13	2.8 ± 0	1.71	21.47 ± 0.27
	50:50	7.54 ± 0.04	5.59 ± 0.17	3.62 ± 0.13	2.45 ± 2.83	1.63	22.63 ± 0.17
	30:70	7.58 ± 0.08	6.47 ± 0.21	4.25 ± 0.17	2.05 ± 1.41	1.54	24.22 ± 0.22
	10:90	7.58 ± 0.14	6.51 ± 0.18	4.33 ± 0.13	2.28 ± 2.12	1.6	23.72 ± 0.06
	0:100	7.6 ± 0.11	6.93 ± 0.15	4.74 ± 0.12	2.38 ± 0.71	1.54	25.2 ± 0.16

3. Results and discussions

3.1. Characterization of substrate and inoculum

Physical and chemical characteristics such as pH, TS, VS, TN, TAN, and C/N of the substrates, substrates with inoculum, and digestate measured in this study are enlisted in Table 1. Biogas production largely depends on the characteristics of substrates and inoculum. CD and PD had lower TS than RS, but their TN was significantly greater than RS (Table 1). Muhayodin et al. [10] also showed the same findings for CD and RS. The C/N ratio is an important factor which affects biogas production from ACoD. A higher C/N ratio inhibits microbial activity because microorganisms require significant nitrogen concentration to grow [41]. C/N ratio of CD, PD, and RS were 32.15 ± 0.03, 14.45 ± 0.07, and 64.15 ± 0.15 (Table 1). According to previous studies C/N ratio of CD, PD, and RS are 25 [36], 10.39 ± 0.06 [40] and 44–74.2 [19], respectively. Different feedstock of livestock might be the reason for the higher C/N ration of CD. According to Dioha et al. [43], suitable C/N ratio for maximum biogas production lies between 20 and 35. To enhance the biogas yield and the methane yield from rice straw by bringing the C/N ratio to its optimum range, it must be co-digested with nitrogen rich animal manure. Most methanogenic microorganisms have an optimum pH level for growth between 6.5 and 8 [44] and are responsible for increased methane production [45]. In the batch assay, the pH of cow dung was slightly higher (8.51 ± 0.02) than the recommended range might be due to the difference in animal feed and source of collection but the addition of co-substrates and inoculum brought balance in pH of different mixing ratio of CD:RS and PD:RS. Inoculum addition with substrates improved the quality of all the test groups for biogas production like pH (6.5–8), TS (7.9 %–10.2 %) and C/N ratio (20–43) (Table 1).

Comparison of characteristics of substrates with inoculum and digestate (Table 1) revealed a drop in VS, which leads to the creation of biogas. All test grouped showed increment of TN (%) in bio-slurry which resulted nutrient enriched fertilizer (Table 1). Abbas et al. [46] and Saha et al. [47] also reported nutrient enrichment occurs during ACoD.

4. Composition of biogas during ACoD

Methane and carbon-dioxide content of biogas during ACoD are shown in Fig. 1a and b for CD:RS and in Fig. 1c and d for PD:RS, respectively.

The average methane content of CD:RS and PD:RS for all the test groups were between 51.39%-53.14 % and 51.47%–57.14 %, respectively (Fig. 1a and c). Carbon dioxide percentage of test groups of CD:RS and PD:RS were between 46.86% and 48.61 %, 42.86%–48.58 %, respectively (Fig. 1b and d). Usually, methane percentage of biogas lies between 40 % and 75 % [48]. So, methane percentages for all test groups were within the range (Fig. 1a and c). During starting of digestion period, the methane content was poor for mono-digestion of CD and PD of all test groups (Fig. 1a and c). Initial lower methane content of different test groups might be due to recalcitrant lignocellulosic structure of RS that is not easily degradable [49]. On the other hand, high methane content was obtained at

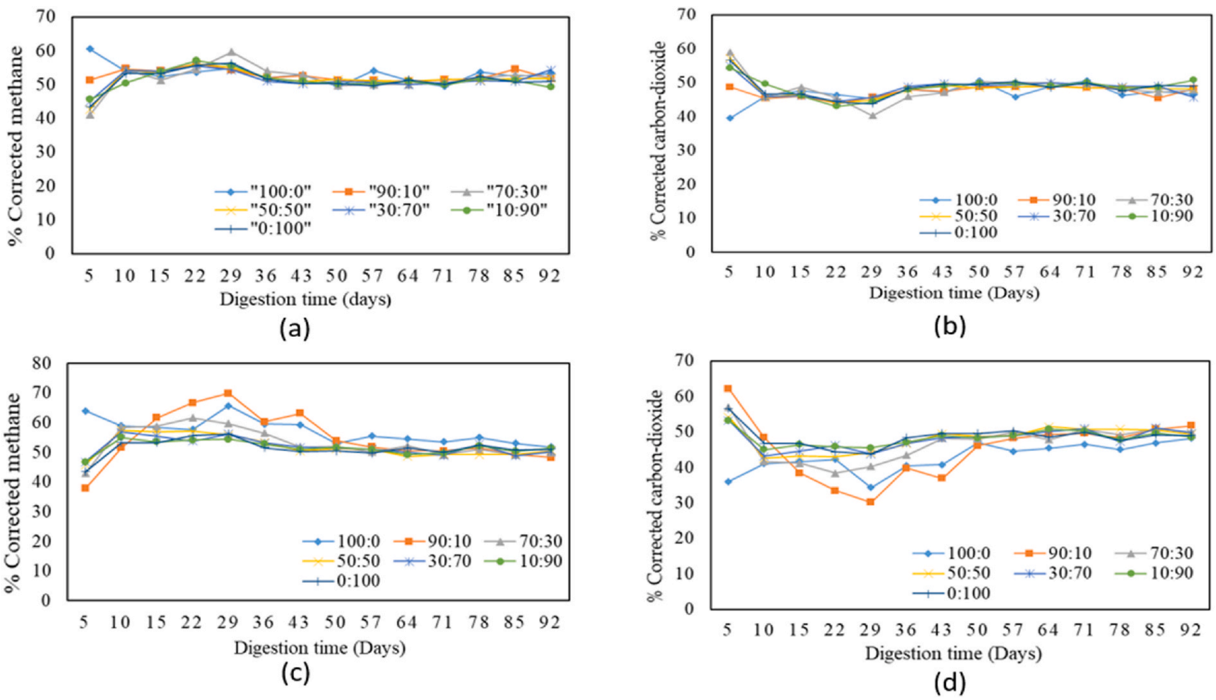

Fig. 1. Biogas composition of different test groups: (a) Methane (b) Carbon-dioxide of different test group of CD:RS and (c) Methane and (d) Carbon-dioxide of different test group of PD:RS.

initial level for CD and PD due to available nutrient content that are required for the growth and reproduction of anaerobic bacteria [50].

4.1. Biogas and methane yield during ACoD

The results of daily and cumulative biogas during the experiment for the test group of CD: RS are shown in Fig. 2a and c, respectively. The highest biogas production was obtained between 29 and 36 days (Fig. 2a) and declined with increasing digestion time due to degradation of volatile solid which was converted into biogas. Gas production from 100:0 ratio of CD and RS was lower than all other test groups. This result might be due to the high ammonia nitrogen. According to Sterling et al. [51] biogas production decreases due to high ammonia nitrogen. The maximum biogas and methane production showed at 70:30 ratio of CD:RS. This was due to the TS (10.18 ± 0.45) and pH (7.58 ± 0.01) of substrates with inoculum (Table 1) was in favourable condition for biogas production. Previous studies showed that optimum value of TS is 10.16 % [52] and pH lies between 6.4 and 7.6 [53] for ACoD which is close to the result obtained from this experiment. Biogas production from a 50:50 ratio was not significant might be due to the higher C/N ratio (42.28) (Table 1) as Puñal et al. [54] recommended to maintain C/N in optimum range (20–35) for AD. The lower percentage of volatile solids in the 0:100 and 30:70 ratios resulted in poor biogas yield compared to the 70:30 ratio although the C/N ratio was optimum. The study showed an increase in biogas at 70:30 ratio of CD and RS were 212.11 % and 38.10 % compared to mono-digestion of CD and RS, respectively. Daily and cumulative methane yield from ACOD of CD:RS are demonstrated in Fig. 2b and d, respectively. Daily methane yield followed the similar trend to daily biogas yield (Fig. 2a and b) and cumulative methane yield also followed similar trend of cumulative biogas yield (Fig. 2c and d). Around 208.12 % and 38.04 % methane production were increased at this ratio compared to AD of only CD and RS, respectively.

Daily biogas, daily methane, cumulative biogas, and cumulative methane yield for the test group of PD: RS are represented in Fig. 3a, b, c and d, respectively. Initially, daily biogas production was low and increased with increasing time as like as ACoD of CD: RS (Figs. 2a and 3a). This might be due to late degradation of RS. The biogas yield obtained from 70:30 and 100:0 was low. This result might be due to higher TN (>1.5) of substrates with inoculum (Table 1) as Song et al. [55] reported higher nitrogen concentration reduces gas production. However, this study resulted in 126.2 ml/gVS biogas yield of PD which was very close to the previous study result (130 ml/gVS) conducted by the SK [56]. Biogas production was inhibited for 10:90 ratio with inoculum due to a higher C/N ratio 41 (Table 1) as high C/N limits methanogenic growth [42]. Biogas production was high for 90:10, 50:50, and 0:100 ratio. This might be due to the favourable condition of ACoD. Maximum biogas and methane yield were obtained at 90:10 ratio of PD:RS. The pH (7.32), TS (9.03 %), VS (7 %), C/N (33.49) (Table 1) of substrates with inoculum were in optimum condition for 90:10 ratio of PD: RS. In this study, a co-digestion ratio of 90:10 improved biogas and methane yields by 173.16 % and 179.30 %, respectively, compared to the AD

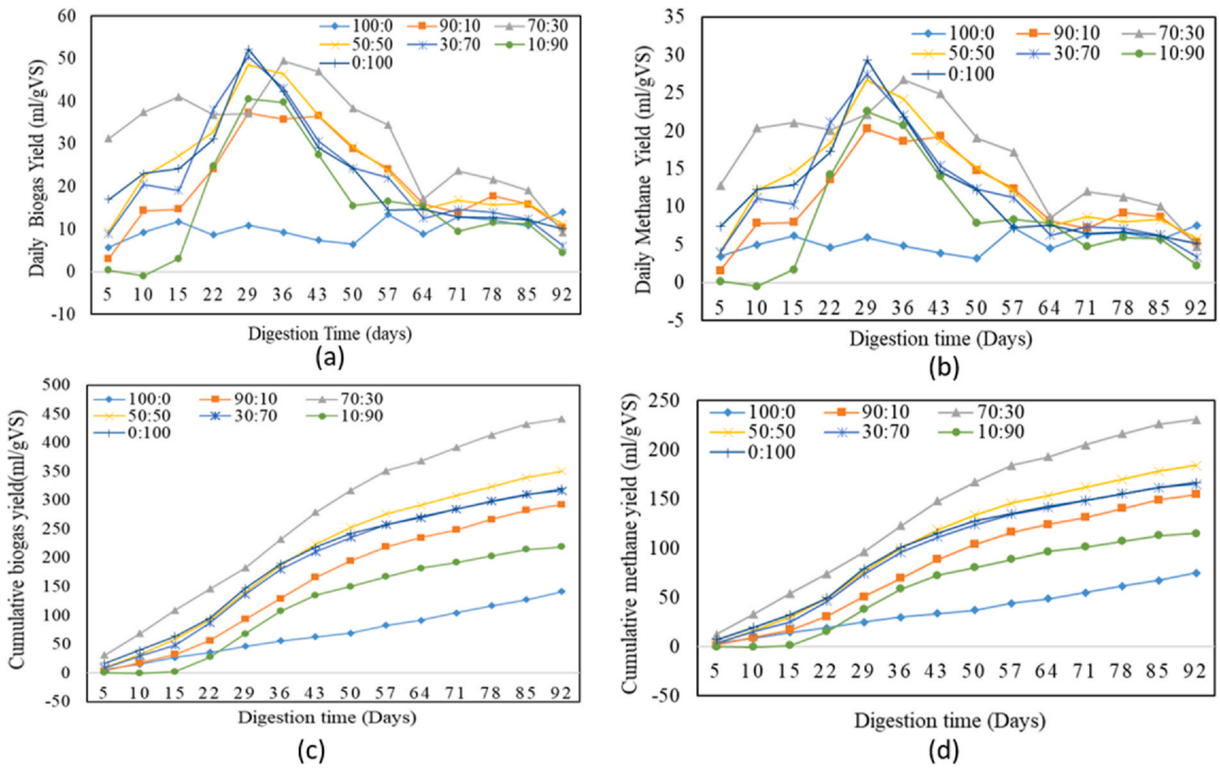

Fig. 2. Daily (a) biogas and (b) methane yield and cumulative (c) biogas and (d) methane yield of different test group of CD:RS.

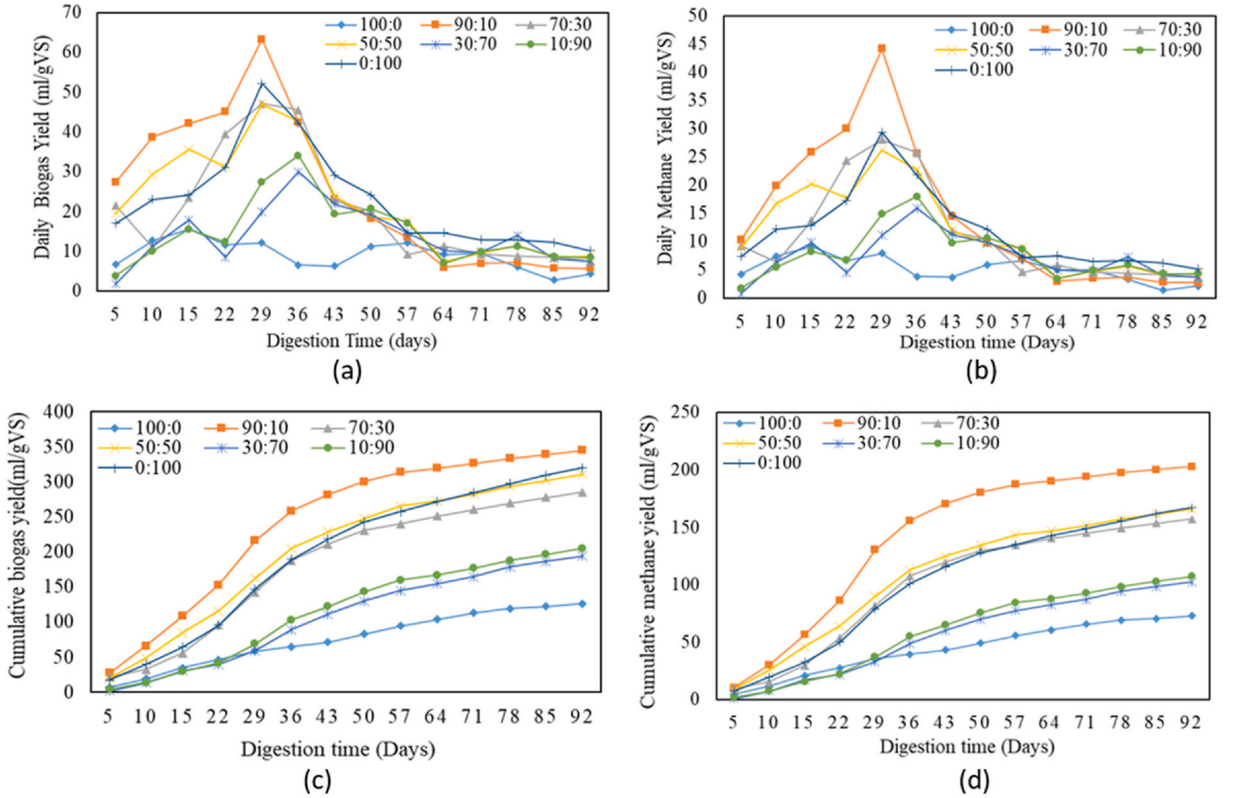

Fig. 3. Daily (a) biogas and (b) methane yield and cumulative (c) biogas and (d) methane yield of different test group of PD:RS.

of PD, and the increment in biogas yields was 7.8 %, compared to the AD of RS only. Methane production for all PD: RS test groups was consistent with the biogas production trend (Fig. 3a and b).

Summary of the cumulative biogas and methane yields for all test groups of CD: RS and PD: RS with standard deviation is presented in Table 2. The ANOVA result showed that mixing at 70:30 ratio of CD and RS and ACoD of 90:10 of PD and RS had a statistically significant effect ($P \leq 0.05$) as compared to other mixing ratios.

4.2. Synergistic effect of methane production during ACoD

Effect of synergy on ACoD of two sets CD:RS and PD:RS are shown in Fig. 4a-e and Fig. 4f-j, respectively. Positive synergy effect indicated higher biogas generation during ACoD of substrates. Positive synergistic effect was observed for all test groups of CD and RS

Table 2
Biogas and methane yield changes during ACoD at different mixing ratio.

Ratio		Cumulative biogas yield (ml/gVS)	Cumulative methane yield (ml/gVS)
CD:RS	100:0	141.5 ± 36.1^{b}	75.0 ± 18.5^{b}
	90:10	$292.5 \pm 124.1^{a,b}$	$154.6 \pm 66.4^{a,b}$
	70:30	441.7 ± 54.1^{a}	231.1 ± 27.9^{a}
	50:50	$350.8 \pm 18.7^{a,b}$	$184.20 \pm 10.27^{a,b}$
	30:70	$316.6 \pm 30.1^{a,b}$	$165.29 \pm 16.07^{a,b}$
	10:90	$218.9 \pm 137.7^{a,b}$	$115.2 \pm 70.5^{a,b}$
	0:100	$319.8 \pm 100.6^{a,b}$	$167.0 \pm 50.8^{a,b}$
	p-value	0.043	0.042
PD:RS	100:0	126.2 ± 33.0^{b}	72.7 ± 20.2^{b}
	90:10	344.8 ± 22.3^{a}	202.97 ± 10.99^{a}
	70:30	$285.1 \pm 45.4^{a,b}$	$157.1 \pm 22.7^{a,b}$
	50:50	$310.8 \pm 104.7^{a,b}$	$165.9 \pm 55.9^{a,b}$
	30:70	$193.9 \pm 56.1^{a,b}$	102.2 ± 29.8^{b}
	10:90	$204.9 \pm 68.7^{a,b}$	$107.1 \pm 36.6^{a,b}$
	0:100	319.8 ± 100.6^{a}	$167.0 \pm 50.8^{a,b}$
	P value	0.013	0.006

N.B: Means with the same alphabets (superscript) are not significantly different at $P \leq 0.05$.

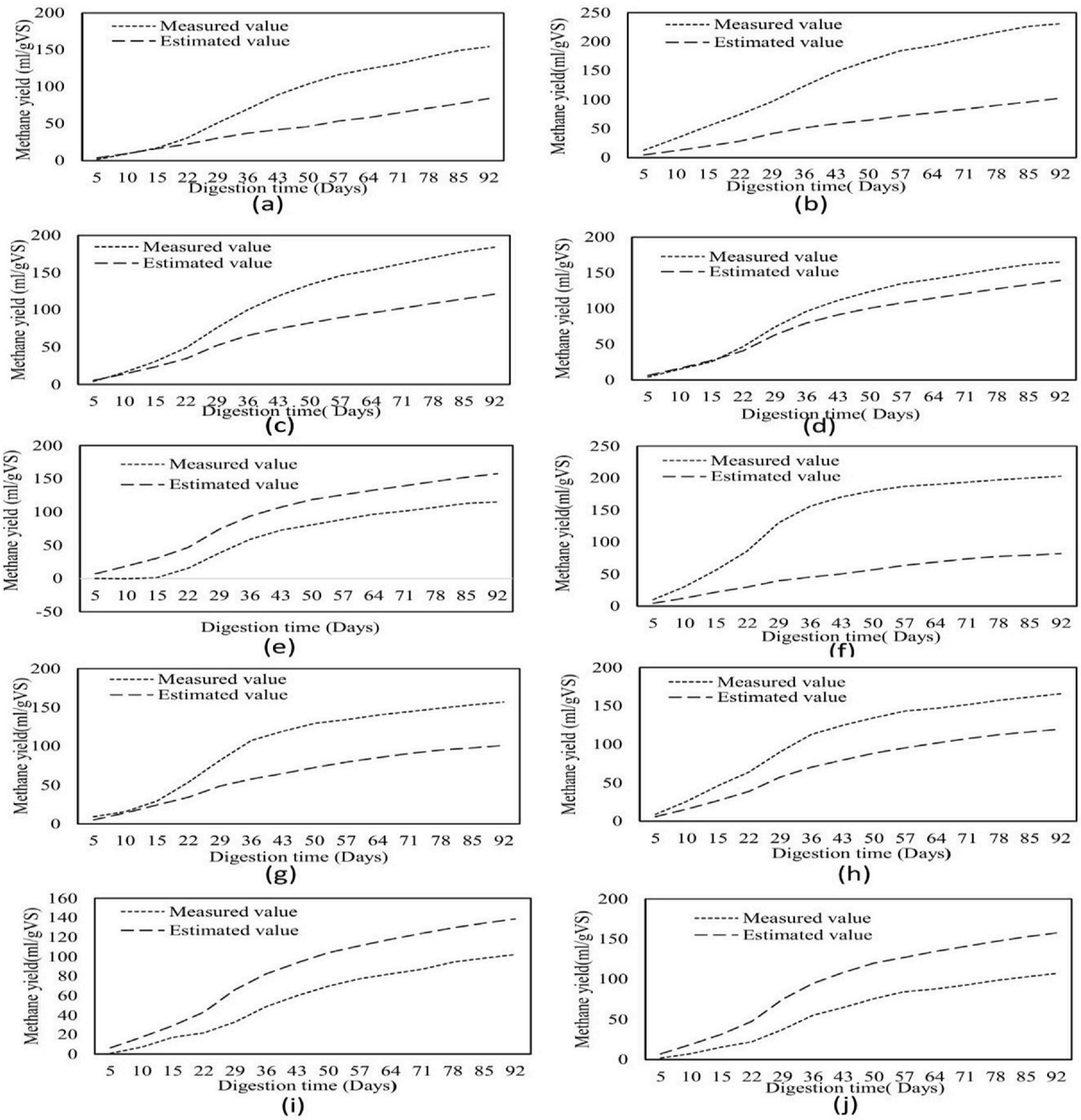

Fig. 4. Synergistic effect (a) 90:10, (b) 70:30, (c) 50:50, (d) 30:70 and e) 10:90 ratio of CD:RS and (f) 90:10, (g) 70:30, (h) 50:50, (i) 30:70 and (j) 10:90 ratio of PD:RS.

except 10:90 (Fig. 4e). Lower measured methane yield for 10:90 ratio might be due to high cellulose, hemicellulose, lignin content in rice straw which exhibited adversarial effect. Except for 10:90 and 70:30 ratio, all test groups of PD and RS had shown a positive synergistic effect (Fig. 4). Khatun et al. [13] also observed positive synergy during ACoD of poultry droppings and banana peel. The highest synergy resulted in the experiment for the 70:30 ratio of CD with RS (225.25 %) (Fig. 4b) and the 90:10 ratio of PD with RS (247.21 %) (Fig. 4f). Consequently, depending on the abundance of substrates, a ratio of 70:30 (CD:RS) and 90:10 (PD:RS) might be recommended for maximum biogas production.

4.3. Kinetics of ACoD process

ACoD of CD and PD with RS at seven different mixing ratios was simulated using three kinetic models: Cone model, modified Gompertz model, and Logistic model. Table 3 demonstrated different parameters derived for these models. Predicted methane yield and experimental methane yield during ACoD of two sets PD: RS and CD:RS are presented in Fig. 5a-g and Fig. 5h-n, respectively.

Table 3
Parameters of kinetic modelling for ACoD.

Cone model for CD:RS							
Parameters	100:0	90:10	70:30	50:50	30:70	10:90	0:100
Bo (ml/gVS)	200	190.7	341.5	220.5	188.8	119.9	193.1
K	0.006597	0.02143	0.01892	0.02479	0.0275	0.02609	0.02813
n	1.22	2.076	1.401	1.899	2.04	3.036	1.855
R^2	0.9882	0.9992	0.9982	0.9991	0.9991	0.9952	0.9977
RMSE	2.628	1.72	3.417	2.028	1.916	3.335	2.87
Modified Gompertz model for CD:RS							
Parameters	100:0	90:10	70:30	50:50	30:70	10:90	0:100
Bo (ml/gVS)	122.9	161.3	245	186.5	165.8	113.1	166
R	0.8505	2.707	3.704	3.382	3.279	2.664	3.227
λ	4.279	10.58	2.465	7.155	7.492	15.79	5.449
R^2	0.9903	0.9983	0.9978	0.9976	0.9975	0.9937	0.9966
RMSE	2.389	2.461	3.781	3.367	3.115	3.819	3.524
Logistic model for CD:RS							
Parameters	100:0	90:10	70:30	50:50	30:70	10:90	0:100
Bo (ml/gVS)	92.13	149.8	229.4	176.5	158.3	108.3	158.6
R	0.9065	2.865	3.792	3.491	3.361	2.761	3.293
λ	7.883	13.16	4.363	9.109	9.208	17.5	7.029
R^2	0.9852	0.992	0.9931	0.9904	0.99	0.9827	0.9899
RMSE	2.951	5.294	6.751	6.696	6.24	6.333	6.083
Cone model for PD:RS							
Parameters	100:0	90:10	70:30	50:50	30:70	10:90	0:100
Bo (ml/gVS)	143.6	200	166	187.4	131.8	125.7	193.1
K	0.01147	0.04451	0.03442	0.03366	0.02073	0.02383	0.02813
n	1.078	2.65	2.275	1.748	1.901	2.118	1.855
R^2	0.995	0.993	0.9971	0.998	0.997	0.9975	0.9977
RMSE	1.734	5.925	3.121	2.606	2.106	2.035	2.87
Modified Gompertz model for PD:RS							
Parameters	100:0	90:10	70:30	50:50	30:70	10:90	0:100
Bo (ml/gVS)	78.24	199.6	153.6	163.1	107.5	109.1	166
R	1.091	5.57	3.692	3.495	1.742	1.972	3.227
λ	4.36E-07	5.408	6.93	3.171	9.015	9.659	5.449
R^2	0.9875	0.9982	0.997	0.9965	0.9965	0.9971	0.9966
RMSE	2.736	3.163	3.188	3.427	2.274	2.206	3.524
Logistic model for PD:RS							
Parameters	100:0	90:10	70:30	50:50	30:70	10:90	0:100
Bo (ml/gVS)	74.73	195.5	148.8	157.9	99.58	102.5	158.6
R	1.03	5.599	3.782	3.476	1.845	2.076	3.293
λ	0.749	6.547	8.425	4.177	11.67	12.03	7.029
R^2	0.9811	0.9946	0.9924	0.9899	0.9911	0.9915	0.9899
RMSE	3.362	5.417	5.101	5.813	3.637	3.754	6.083

Cone model fitting resulted R^2 greater than 0.99 and low value root mean square error (RMSE) (Table 3) but deviation between expected and experimental methane yield was greater than 15.5 % for all test groups. However, according to Paulose & Kaparaju [57] the deviation between expected and experimental values greater than 10 % results interrupted prediction of AD processes. So, the Cone model was not accepted for the co-digestion of CD and RS. Both modified Gompertz model and Logistic model were well suited (Fig. 5) as R^2 was greater than 99 % (Table 3). However, RMSE and λ of modified Gompertz model was lower than Logistic model (Table 3). A lower positive value of λ implied faster degradation as the positive value of λ showed the least time requirement for starting the bio-methanation process [13]. According to Zaidi et al. [40] and Budiyono et al. [58] R^2 should be above 99 % and RMSE should be less than 10 % for well model fitting and Khatun et al. [13] reported Cone model was suitable for predicting ACoD process for poultry droppings with banana peel at different mixing ratio due to lower value of RMSE and higher degradation velocity. So, modified Gompertz model was best suited for predicting ACoD of CD and RS. Cone model showed the highest deviation between predicted and experimental yield (Fig. 5h -n) and was between 12.95% and 97.5 % which resulted in rejection of the Cone model for predicting methane yield. Parameters of modified Gompertz model and Logistic model showed similar trends as like as parameters of ACoD of CD and RS (Table 3). In the study, all the models had correlation co-efficient (R^2) above 99 % and RMSE less than 10 % for both co-digestion cases might be allowed to fit well with the experimental result but in the case of prediction of methane yield accurately modified Gompertz model showed a satisfying result. The value of R found from the Gompertz model indicated maximum daily methane yield which might be considered during the design of a biogas storage unit in a continuous reactor on an industrial scale. The lag phase showed microbial adaptation rate which might help in considering hydraulic retention time for biogas production.

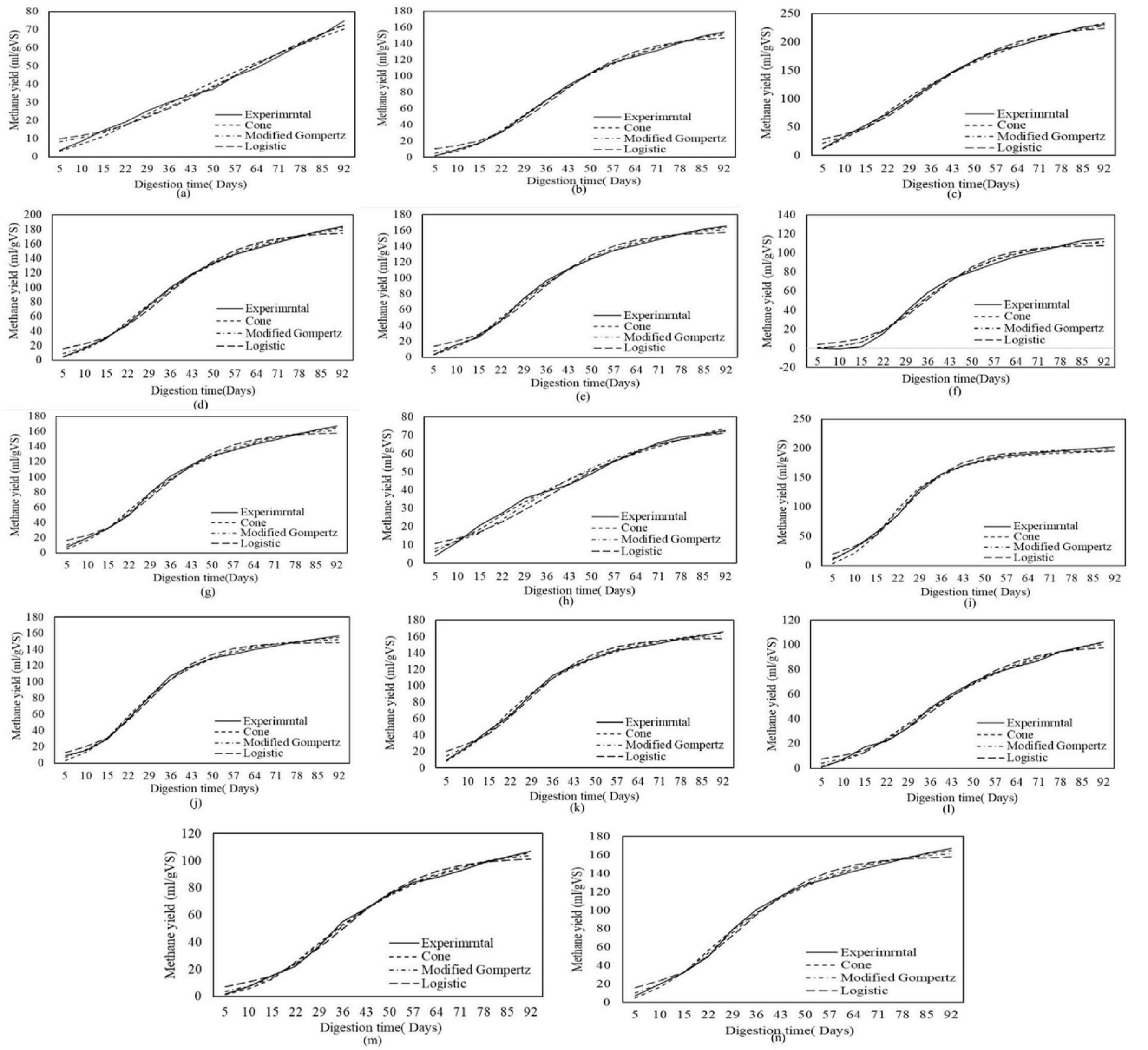

Fig. 5. Measured and predicted methane yields (a)100:0, (b) 90:10, (c) 70:30, (d) 50:50, (e) 30:70, (f)10:90 and (g) 0:100 ratio of CD:RS and (h) 100:0, (i)90:10, (j)70:30, (k) 50:50, (l) 30:70, (m)10:90 and (n) 0:100 ratio of PD:RS.

5. Conclusion

The batch assay for ACoD of CD and PD with RS showed that addition of RS with CD and PD maximizes biogas and methane production. Abundant production of CD and PD promoted mono-digestion of these animal manures in Bangladesh. But, addition of lignocellulosic agricultural by-product RS with CD and PD showed an increase in the bio-methane potential of these wastes with positive synergy and simultaneously solved the waste management problem. In the research, maximum biogas and methane yields for ACoD of CD and RS were at the 70:30 ratio. On the other hand, the co-digestion set of PD and RS produced the highest biogas and methane yields at the ratio of 90:10. In the case of kinetic modelling, the modified Gompertz model was the most suited model to forecast biomethane production from anaerobic co-digestion of RS with CD and PD, respectively. Process parameters found from kinetic modelling might contribute to establishing a commercial-scale continuous digester for ACoD of RS with CD and PD. To enhance biogas production and reduce retention time, pre-treatment of RS is recommended to increase the hydrolysis rate. ACoD of CD and PD with other lignocellulosic waste available in Bangladesh may also be utilized to maximize gas production from CD and PD. Biogas production on a commercial scale from ACoD of CD with RS and PD with RS may contribute to enhancing renewable energy production, and reducing environmental hazards through proper management of these wastes.

CRediT authorship contribution statement

Chayan Kumer Saha: Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Jannatoon Nime:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Mst. Lucky Khatun:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Tafura Hoque Sharna:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Md. Monjurul Alam:** Writing – review & editing, Resources.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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