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Co-Digestion-Based Circular Bio-Economy to Improve Biomethane Generation and Production of Nutrient-Enriched Digestate in Bangladesh

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Abstract: Anaerobic co-digestion (ACoD) of cow dung (CD) and maize cob (MC) may be envisaged as the best way to enhance biomethane formation and production of nutrient-enriched fertilizer for the implementation of a circular bio-economic system. The study aimed to find out the optimum ratio for the highest biogas production to produce heat and energy and also the generation of nutrient-enriched organic fertilizer to use in crop land. A batch study was carried out for 99 days in an incubator maintaining 35 ± 1 °C temperature for seven different test groups of CD and MC (100:0, 90:10, 70:30, 50:50, 30:70, 10:90, and 0:100). The highest biogas production (356.6 ± 21.2 mL/gVS) was at 50:50 ratio with 138.05% and 32.02% increments compared to the digestion of CD and MC alone, respectively. Kinetic modeling showed the best fit using a Logistic model to evaluate ACoD of CD and MC mathematically. ACoD of available CD and MC in Bangladesh could produce 716.63 GWh/yr electricity for consumption and a large volume of nitrogen-enriched fertilizer to use in nitrogen-deficit soil. There was no significant difference in nutrient enrichment among different test groups. Awareness about ACoD technology and proper use of digestate might bring this technology to field-level utilization and thus help to implement the circular bio-economic concept through zero waste generation.

Keywords: co-digestion; circular bio-economy; cow dung; maize cob; quality digestate; kinetic modeling

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1. Introduction

The livestock sector plays a significant role in the development of a country by meeting the demand of nutrients and facilitating improved livelihood [1]. The livestock sector in a developing country like Bangladesh includes animals, namely cow, goat, sheep, buffalo, poultry, etc. [2]. This sector has around 1.85% contribution to the GDP of Bangladesh [3]. Dairy farming among various subsectors of livestock farming in Bangladesh has become a significant source of fulfilling protein demand and reducing poverty [4]. In Bangladesh, the annual production of cows is nearly 29.45 million. On average, dairy farming produces around 12.3 million tons of cow dung annually [5]. Managing such a huge amount of cow dung has become a great concern. Some indigenous cow dung management practices include burning, cleaning material, and insect repellent [6]. Cow dung burning in open stoves causes the emission of greenhouse gases (GHGs), organic substances, and particulate materials [7]. Direct contact of air with cow dung due to open dumping and use as cleaning material or insect repellent causes GHG emission, odor problems, water pollution, and negative impacts on the environment [8,9].

The sustainable and proper management of cow dung is important to ensure a safe and quality environment for animals and plants. Anaerobic digestion is a green energy generation process that facilitates biogas production from cow dung along with quality digestate. Cathy et al. [9], Olaoye et al. [10], Saibur et al. [11], Onwukeme et al. [12], Putri et al. [13], and Ukpai et al. [14] reported cow dung as a suitable substrate for anaerobic digestion to produce bio-energy. However, mono-digestion of cow dung results in lower gas yield due to nutrient imbalance, presence of significant non-biodegradable materials on dairy manure composition, and poor microbial activity [15]. The performance of AD technology largely depends on biogas yield, process stability, degradation rate of organic matter, digestate quality, and proper digestate management [16]. So, anaerobic co-digestion (ACoD) of cow dung with another carbon-enriched substrate may increase biogas yield through nutrient balancing and enhancing microbial activity. ACoD is a technique in which microbial breakdown of two or more substrates occurs simultaneously in the absence of oxygen when substrates are mixed to augment the digestion process and improve gas yield. Co-digestion increases biogas yield and improves the quality of biogas and digestate through nutrient balancing by mixing substrates at an optimum ratio while using different additives [17–21], enhancing the digestion process. It is further observed that co-digestion not only increases biogas yield but also maintains digestate stability [22]. Nowadays, researchers are focusing on ACoD due to its superiority [23–25]. Several studies showed that anaerobic co-digestion of cow dung with fruit waste [26], waste leaf [27], elephant grass [28], food waste [29], lignocellulosic crop residue [30], and aquatic waste [31], respectively, enhanced biogas and methane yield. Lignocellulosic crop residues contain a higher percentage of carbon; on the other hand, cow dung contains a higher percentage of nitrogen, so anaerobic co-digestion of these two wastes may be best suited for nutrient balancing and enhancing biogas yield from cow dung. Major crop production in Bangladesh includes rice, wheat, maize, jute, sugarcane, pulse, and vegetables [32], which causes the production of lignocellulosic residues like rice straw, wheat straw, maize cob, etc. Rice straw and wheat straw can be used as animal feed and animal bedding, but open dumping and burning of maize cob is a common practice in Bangladesh. Every year, vast amounts of lignocellulosic waste like maize cob are produced during maize cultivation in developing countries like Bangladesh. Around 4.26 million metric tons of maize was produced in Bangladesh [2], which results in 0.92 million ton of maize cob waste. Maize cob is a hard and less biodegradable lignocellulosic waste that has lower contribution as soil amendments [33] and burning it for cooking causes GHG emissions. This high-carbon-contained maize cob can be used as a co-substrate during manure digestion [34]. Increased volume of biogas from anaerobic co-digestion of cow dung and maize cob can be used for lighting, heating, and cooking, and upgraded biogas can also be injected into the national gas grid. Digestate slurry produced from co-digestion can also be utilized as nutrient-enriched soil amendments, which will indirectly help in increasing crop yield, and a solid portion of digestate can be used for animal bedding. Multiple uses of bio-energy and digestate from anaerobic co-digestion for living beings' welfare and environment will transform the linear system of the waste managing system into a circular bio-economic system. Circular bio-economy is a system of material recovery in which waste from one production system is used as input material for another system [35]. So, ACoD of CD and MC can promote circular bio-economy by using waste from agricultural production systems as the input material for bio-energy production systems and fulfill sustainable development goal 7 (Affordable and Clean Energy). Abdoli et al. [36] and Adebayo et al. [37] reported that co-digestion of maize with CD and maize cob with pig manure enhances biogas generation, respectively. Adebayo et al. [38] found that co-digestion of CD and MC at a mesophilic condition increased biogas production significantly along with enhanced biomethane generation.

However, comprehensive studies showed a lack of information about the proper mixing ratio of CD and MC to maximize the biogas yield and nutrient quality of the digested slurry along with the contribution to the circularity of the bio-economic system.

Forecasting of biomethane generation from ACoD is also limited. Hence, this study aimed to find the optimum ratio for biogas production from ACoD of CD and MC, forecasting the ACoD process and investigating the contribution of ACoD of CD and MC in the circularity of bio-economy based on the proposed approach.

2. Materials and Methods

2.1. Process Description

An anaerobic co-digestion process-based circular bio-economic system is illustrated in Figure 1. During maize cultivation, maize cob is produced as by product and maize leave can be used as dairy feed. Maize cob and cow dung from dairy farm can be co-digested to maximize biogas production through nutrient balancing and due to synergy of digestion process. This increased volume of biogas can be used in CHP (Combined Heat and Power) unit for electricity and heat generation. Waste heat from CHP can be used to maintain optimum temperature in digester. Electricity produced from CHP unit can be used in animal farm and household of village. Heat produced from CHP can also be used for drying of grain. Biogas can also be used directly for cooking and up-gradation of biogas, facilitating contribution to natural gas grid. Digestate produced in ACoD can also be an input in production systems such as nutrient-enriched fertilizer in crop fields. Hence, co-digestion may create a close nexus of crop and livestock production along with energy production and facilitate the implementation of a circular bio-economy.

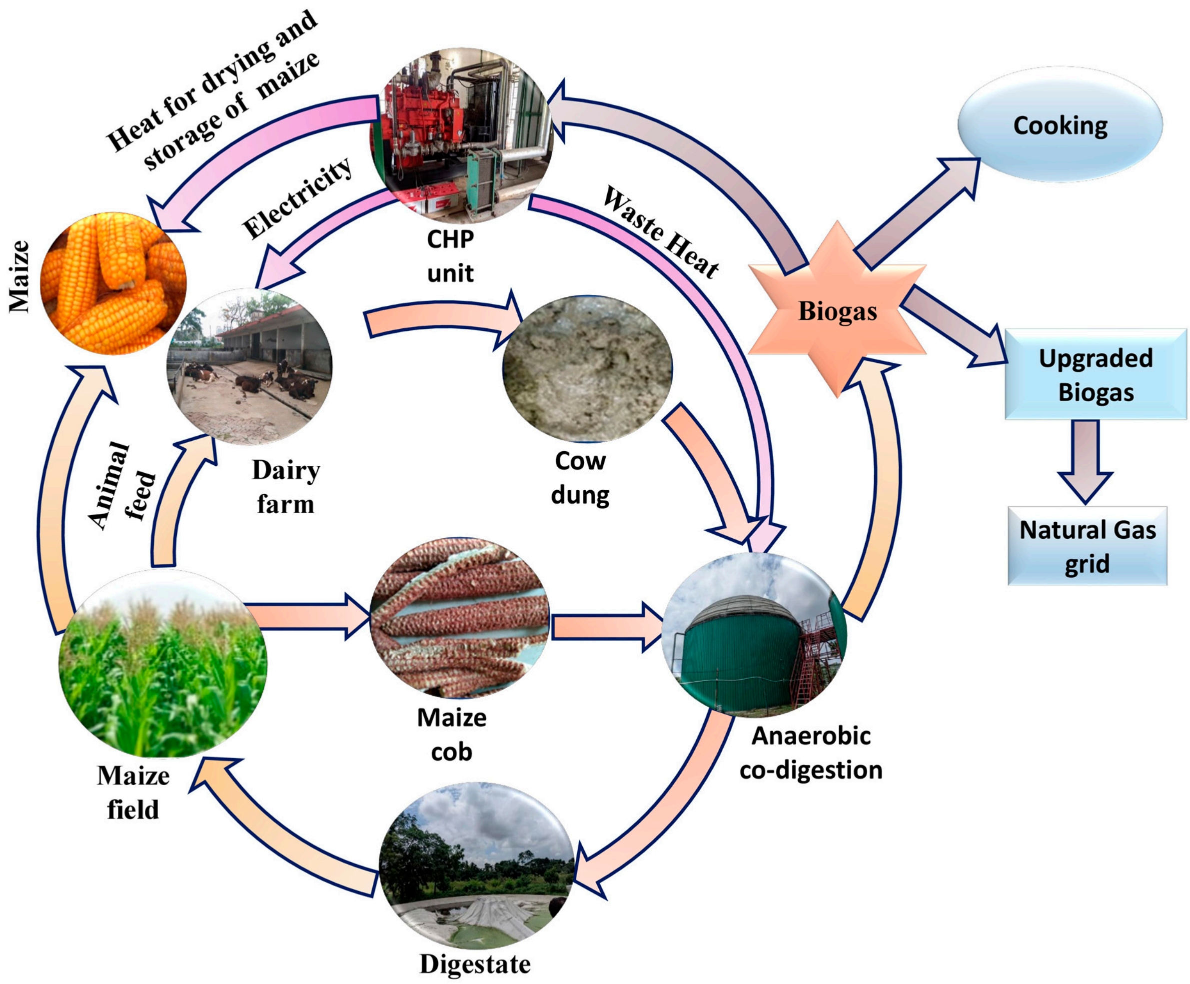

Figure 1. Circularity of anaerobic co-digestion system on cow dung and maize cob.

2.2. Collection of Substrate and Inoculum

This batch study was conducted at the Green Energy Knowledge Hub (GEKH), Department of Farm Power and Machinery, Bangladesh Agricultural University (BAU), Mymensingh, Bangladesh. Cow dung was collected from the dairy farm, BAU. Maize cob was collected from the local market of Jamalpur, Bangladesh. Sludge of 30-day-digested cow dung from Continuous Stirred Tank Reactor of GEKH, BAU, was used as inoculum. The inoculum was kept in an incubator for 15 days to inhibit methane production from the inoculum during the batch study. Pretreatment of the substrate increased surface area and degradability rate [39], which is why maize cob was ground to reduce particle size before it was used as feedstock for faster hydrolysis during digestion.

2.3. Analytical Methods

Characteristics of substrates were analyzed including pH, total solid (TS), volatile solid (VS), ash, nitrogen (N), total ammonium nitrogen (TAN), and carbon: nitrogen (C/N) ratio. pH of all biomass was measured using pH meter (MW 150 Milwaukee pH meter). TS, VS, and ash were determined following the procedure described by APHA [40]. The micro-Kjeldahl method [41] was used to determine N, P and K of substrates were determined following the colorimetric method [42] and flame emission spectrophotometric method [43], respectively. TAN was measured using a photometer (NOVA 60, Memmert, Germany). C/N was determined following Equation (1) [44].

$$\mathrm{C/N} = \mathrm{VS}_{\mathrm{db}(\%)}/1.76 \times \mathrm{N} \tag{1}$$

where $\mathrm{VS}_{\mathrm{db}(\%)}$ is the dry basis volatile solid.

Glass syringe (SGC, Australia, capacity: 500 mL) was used to determine the volume of biogas, periodically. The biomethane potentiality of each biomass was analyzed using a gas analyzer (Optima 7 Biogas MRU Instruments, Inc., Humble, TX, USA) for methane (%), carbon dioxide (%), hydrogen sulphide (ppm), and a trace amount of oxygen (%) present in biogas produced during AD of biomass. Periodical biogas volume and gas composition were recorded in MS Excel sheet for further data interpretation to know each biomass's biomethane potential.

2.4. Experimental Setup

Anaerobic digestion of all biomass was carried out using 500 mL batch bottles as digesters. Batch bottles were air-tightened using butyl rubber stoppers. The amount of biomass was calculated following Equation (2) [24].

$$P_i = M_i \times C_i / M_s \times C_s \tag{2}$$

where P_i is VS ratio, which is equal to 1. M and C denote mass (g) and VS (g). The subscripts i and s are denoted for inoculum and substrate, respectively. Oxygen was removed by nitrogen flushing for 2 min.

Biomass was added with 250 g inoculum homogeneously. Then, closing with butyl rubber stopper batch, bottles were flushed with nitrogen gas for two minutes to maintain anaerobic condition. All the samples were triplicated for this experiment. Batch bottles were placed in an incubator (Model: ICP 110; manufacturer: Merck, Germany; volume: 108 L) maintaining mesophilic condition (35 ± 1 °C) for 71 days of digestion period. Methane production from inoculum was subtracted from methane production of each substrate during the experiment. The actual biomethane potential of each biomass was calculated using Equation (3) [5].

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

where $BMP_{observed}$ is the biomethane (mL/gVS) potential of biomass, $V_{(ino+biomass)}$ is the volume of methane (mL) from biomass with inoculum, V_{ino} is the volume of methane (mL) from inoculum, and $mVS_{biomass}$ (gVS) is the mass of volatile solid of biomass added during AD.

2.5. Kinetic Analysis

Kinetic modeling of biogas production trends with digestion times helps to forecast biogas production potentiality and AD efficiency [45]. BMP potentials from all biomass were fitted with first-order model (4) [24], cone model Equation (5) [24], modified Gompertz model Equation (6) [46], and logistic model Equation (7) [47], respectively, to know different kinetic parameters related to AD process of organic substrates.

$$B_{(t)} = B_o \times \left(1 - e^{-kt}\right) \tag{4}$$

$$B(t) = \frac{B_o}{1 + (Kt)^{-n}} \tag{5}$$

$$B_{(t)} = B_o \exp\left\{-\exp\left[\frac{R_{max} \times e}{B_o}(\lambda - t) + 1\right]\right\} \tag{6}$$

$$B_{(t)} = \frac{B_o}{1 + \exp\left[4R_{max}\frac{(\lambda - t)}{B_o} + 2\right]} \tag{7}$$

where $B_{(t)}$ is biomethane potential at time t (d) (mL/gVS), B_o is the highest biomethane potential of a biomass (mL/gVS), k is degradation rate (d^{-1}), the value of e is 2.7183, n is the shape factor, R_{max} is the highest biomethane potential of substrates per day (mL/gVS d^{-1}), and λ is lag phase (d). Kinetic models were fitted for experimental data using nonlinear curve fitting toolbox of MATLAB (R2018a).

2.6. Electricity and Heat Production

Heat and electricity generation are the typical uses of biogas generated from anaerobic co-digestion in commercial scale biogas plants to mitigate the energy shortage issue. Thus, with a sustainable renewable energy source and efficient waste-to-energy conversion, the process can convert to a circular bio-economic system. Potential waste production during animal farming and maize cultivation were calculated following Equations (8) and (9) [48].

$$W_c = N \times RGR \tag{8}$$

$$W_m = P \times RYR \times RRF \times SAF \tag{9}$$

where W_c is the net cow dung production (kg/yr), W_m is the net available maize cob (kg/yr), N is the number of cows available in Bangladesh, RGR is the CD production rate (kg/yr), P is the maize production in Bangladesh, RYR is the MC-to-maize yield ratio, RRF is the MC recovery factor, and SAF is the surplus MC availability factor. In this study, RGR was considered based on 8.87 kg/day CD production per cow [49]. The values of RYR, RRF, and SAF for substrates were considered from Rahman et al. [48] during calculation.

Potential biogas electricity and heat production from co-digestion of CD and MC were calculated following Equations (10)–(12), respectively.

$$BG = bg \times W_{cm} \times VS_{cm} \tag{10}$$

$$Electricity\left(\frac{MJ}{yr}\right) = BG \times C_v\, of\, biogas \times Electrical\, efficieny\, of\, CHP\, unit \tag{11}$$

$$Heat\left(\frac{MJ}{yr}\right) = BG \times C_v\, of\, biogas \times Heat\, efficieny\, of\, CHP\, unit \tag{12}$$

where BG is the potential biogas production from co-digestion of available CD and MC at optimum ratio (m^3/yr), bg is the cumulative biogas production potential from ACoD of CD and MC from this batch study (m^3/kgVS), W_{cm} is the mass of CD and MC (available in

Bangladesh) at optimum ratio, VS_{cm} is the volatile solid content of CD and MC at optimum ratio, and C_v is the calorific value of biogas. In this study, heat and electricity generation from anaerobic co-digestion of cow dung and maize cob available in Bangladesh was calculated based on the CHP unit (GE Jenbacher gas) with 36.3% electrical and 44.4% heat efficiency [50]. Calorific value of biogas was considered as 22 MJ/m^3 [51]. Waste heat produced during CHP operation was not calculated. During calculation of energy and heat generation, the energy requirement for CHP operation was not considered.

2.7. Nutrient Analysis of Digestate

Anaerobic co-digestion is a technology which increases the nutrient quality of digestate compared to raw substrate [35]. Nutrient-enriched digestate could be used in crop fields, which will facilitate the conversion of waste to nutrients for plants and reduce the use of organic fertilizer, thus developing a circular bio-economic system. Nutrient content of digestate was found following Equation (13).

$$NC = Digestate \times TS\ (\%) \times nc\ (\%) \tag{13}$$

where *NC* is the nutrient content (kg/yr), Digestate is the amount of slurry after digestion (kg/yr), *TS* (%) is the total solid percentage of digestate, and *nc* (%) is the nutrient percentage in digestate based on total solid.

3. Results and Discussion

3.1. Characterization of Substrate during ACoD

The physical and chemical composition of substrates and feedstock (substrates with inoculum) are listed in Table 1. Biomethane generation largely influenced by the initial properties of substrates and inoculums. In this batch assay, pH levels of raw CD and MC were about 7.59 and 7.55 (Table 1), respectively. Previous studies resulted in pH levels of CD and MC of 7.08 [44] and 6.83 [52], respectively, which were close to the value of the samples used in this experiment. This slight difference might be due to the source of waste collection. The production of biogas from ACoD significantly depends on the C/N ratio [24]. TS of cow dung and maize cob (Table 1) was nearest to the previous study with percentages of 17.30% [44] and 82.85% [53]. The C/N ratio of CD and MC were 32.15 and 42.72, respectively. According to previous studies, the C/N ratios of CD and MC were 25 [54] and 49.19 [55], respectively. The C/N ratio might be due to difference in feed of cow dung, source of maize cob collection, and method of C and N determination. Comparison of characteristics of substrates and feedstock showed that when substrates mixed with inoculums, the physical and chemical characteristics changed. The addition of inoculum brought the pH of all test groups in between 7.20 and 7.5, which was the nearest to optimum for ACoD, as Rabi et al. [23] reported optimum pH for biogas production is between 6.5 and 7.2. When substrates were mixed with inoculums, the TSs of all test groups were in between 8 and 11.5% (Table 1), which was favorable for biogas production, as according to Budiyono et al. [56], optimum TS for biogas production is from 7 to 9%. TAN, which has an adverse effect on AD process, was also reduced when substrates mixed with inoculum. The addition of inoculum brought the C/N ratio of substrates in between 31.83 and 39.84, which is slightly higher than the optimum range (20–30). This might not cause any major impact as optimum range of C/N ratio may vary depending on the substrates from 9 to 50, as reported by Guarino et al. [57]. Furthermore, Rahman et at. [5] observed optimum gas production at 32.02 C/N ratio during co-digestion of poultry droppings and wheat straw.

Characteristics of digestate after 99 days of digestion are shown in Table 2. Comparison of Tables 1 and 2 showed a lower value of VS in digestate, which indicated degradation of substrates and production of biogas. An overall increase in the N percentage was observed in digestate (Table 2) compared to that of parent feedstock (Table 1). This implies that nutrient concentrations are getting higher in digestate for ACoD under these conditions.

Table 1. Characteristics of raw substrates and feedstock.

Characteristics of raw substrates								
Substrates		**pH**	**TS (%)**	**VS_{wb} (%)**	**Ash (%)**	**TAN (g/L)**	**N (%)**	**C/N**
CD		7.59 ± 0.02	13.45 ± 0.37	11.30 ± 0.31	15.98 ± 0.05	4.15 ± 0	1.49	32.15 ± 0.92
MC		6.55 ± 0.04	87.77 ± 1.42	83.16 ± 1.29	5.26 ± 1.24	0.68 ± 0	1.26	42.72 ± 0.64
Inoculum		7.29 ± 0.02	7.01 ± 0.29	4.85 ± 0.15	30.83 ± 0.16	2.18 ± 0.01	1.26	31.19 ± 0.93
Characteristics of feedstock								
Mixing Ratio		**pH**	**TS (%)**	**VS_{wb} (%)**	**Ash (%)**	**TAN (g/L)**	**N (%)**	**C/N**
CD:MC	100:0	7.41 ± 0.05	9.07 ± 0.15	6.75 ± 0.30	2.32 ± 0.15	2.75 ± 0.02	1.328	31.83 ± 0.94
	90:10	7.34 ± 0.04	8.65 ± 0.34	6.56 ± 0.22	2.09 ± 0.12	2.65 ± 0.01	1.300	33.13 ± 0.22
	70:30	7.28 ± 0.07	9.10 ± 0.14	7.42 ± 0.08	1.68 ± 0.05	2.33 ± 0.03	1.280	36.18 ± 0.19
	50:50	7.32 ± 0.03	9.24 ± 0.05	7.74 ± 0.04	1.51 ± 0.01	1.98 ± 0.02	1.270	37.44 ± 0.03
	30:70	7.24 ± 0.06	10.00 ± 16	8.62 ± 0.04	1.38 ± 0.02	1.83 ± 0.01	1.265	38.71 ± 0.02
	10:90	7.24 ± 0.03	11.22 ± 0.03	9.92 ± 0.01	1.30 ± 0.01	1.88 ± 0.03	1.261	39.84 ± 0.05
	0:100	7.20 ± 0.07	10.68 ± 0.06	9.02 ± 0.11	1.65 ± 0.05	2.08 ± 0.02	1.260	38.10 ± 0.29

Table 2. Characteristics of digestate.

Mixing Ratio		**pH**	**TS (%)**	**VS_{wb} (%)**	**Ash (%)**	**TAN (g/L)**	**N (%)**	**C/N**
CD:MC	100:0±	6.92 ± 03	7.22 ± 0.47	5.42 ± 0.47	1.80 ± 0.16	2.13 ± 0.02	1.71	24.96 ± 0.81
	90:10±	6.83 ± 0.08	6.30 ± 0.21	4.84 ± 0.17	1.46 ± 0.06	1.98 ± 0.01	1.48	29.40 ± 0.25
	70:30±	6.73 ± 0.05	6.41 ± 0.19	4.93 ± 0.16	1.48 ± 0.06	1.75 ± 0.02	1.62	26.90 ± 0.24
	50:50±	6.80 ± 0.06	6.82 ± 0.29	5.48 ± 0.0.28	1.33 ± 0.04	1.60 ± 0.03	1.76	25.91 ± 0.23
	30:70±	6.86 ± 0.07	7.14 ± 7.14	5.74 ± 0.28	1.39 ± 0.02	1.78 ± 0.01	1.09	41.86 ± 0.16
	10:90±	6.91 ± 0.04	7.86 ± 0.15	7.42 ± 0.24	1.47 ± 0.08	1.73 ± 0.02	1.57	29.46 ± 0.45
	0:100±	6.87 ± 0.05	6.26 ± 0.36	4.94 ± 0.37	1.31 ± 0.02	1.78 ± 0.03	1.62	27.63 ± 0.47

3.2. Analysis of Biogas Composition

Biogas composition including methane, carbon dioxide, and hydrogen sulphide are demonstrated in Figure 2a–c, respectively. Methane and carbon dioxide have a major portion in biogas mixture, and the other components are present in small amounts depending on substrate characteristics, as Czekała et al. [58] reported substrates with higher portions of carbohydrate and protein have a high hydrolysis rate, but substrates with fat have a comparatively high methane content in biogas. Methane contents of biogas produced from 100:0, 90:10, 70:30, 50:50, 30:70, 10:90, and 0:100 test groups were 52.78%, 51.80%, 51.68%, 51.76%, 51.25%, 51.15%, and 51.61%, respectively (Figure 2c). Khatun et al. [24] found methane content in a range of 36–58% during co-digestion of animal manure and fruit waste. So, methane content of biogas during anaerobic co-digestion was within the range for using an energy source, which is in accordance with the findings of Fagerström et al. [59]. Percentages of carbon dioxide of all test groups of CD and MC were in between 45% and 55% (Figure 2b). Nandi et al. [44] also reported carbon dioxide content in between 25% and 50% during digestion of cow dung at different temperatures. Carbon dioxide content was suddenly increased in between 92 and 99 days of digestion, and it might be due to the poor activity of methanogenic microbial group that converts carbon dioxide into methane. Co-digestion significantly reduced the hydrogen sulphide content of biogas for all test groups (Figure 2c), which was beneficial as hydrogen sulphide hinders the growth of methanogenic bacteria [60].

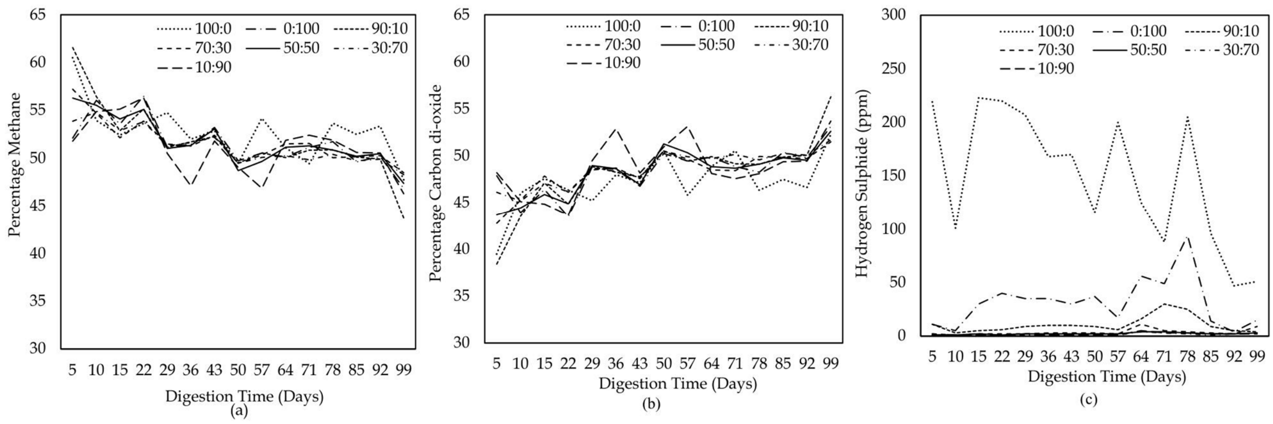

Figure 2. Composition of biogas (**a**) methane, (**b**) carbon dioxide, and (**c**) hydrogen sulphide.

3.3. Daily Biogas and Methane Production

Biogas and methane production from all test groups of CD and MC per day during ACoD process is demonstrated in Figure 3a,b, respectively. Daily methane production followed a similar trend to biogas yield (Figure 3a,b). From Figure 3, the biogas production was low at 5 days of digestion time and then increased significantly. An initial lower biogas might be due to slower activity of microorganism and lower hydrolysis rate, as raw substrates were used as feedstock without any chemical or biological pretreatment to speed up hydrolysis in the lignocellulose. Biogas yield was high for all test groups in between 10 and 50 days and then reduced gradually. The conversion of volatile solids into biogas might be the cause of the reduced daily production after 50 days. The highest daily biogas and methane yield was found in the 10th and 36th days of digestion (Figure 3). These peaks might be due to breakdown of carbohydrates and complex organic compounds, respectively. Wang et al. [47] also reported two peaks during biogas production from cow dung for carbohydrates decomposition and breakdown of organic molecules, respectively.

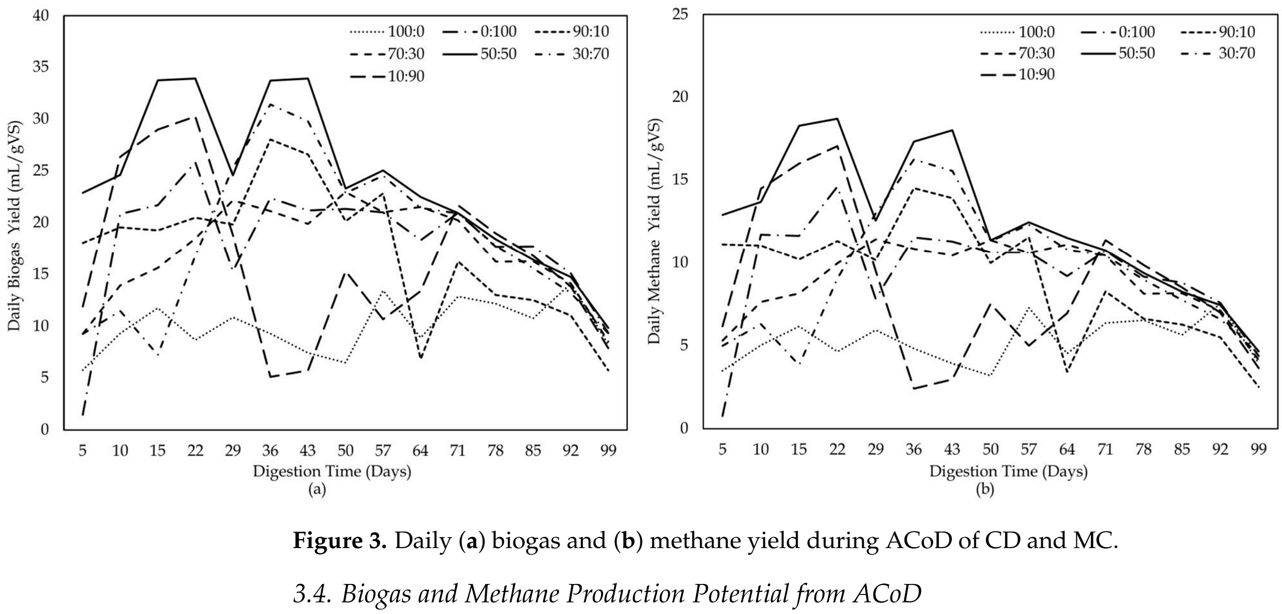

Figure 3. Daily (**a**) biogas and (**b**) methane yield during ACoD of CD and MC.

3.4. Biogas and Methane Production Potential from ACoD

Cumulative biogas and methane yield from this co-digestion study for all test groups of CD and MC is demonstrated in Figures 4a and 4b, respectively. Biogas production from 100:0, 90:10, 70:30, 50:50, 30:70, 10:90, and 0:100 test groups of CD and MC were 149.8 ± 36.1, 260.0 ± 16.7, 261.3 ± 38.5, 356.6 ± 21.2, 276.8 ± 56.7, 245.6 ± 34.9, and 270.1 ± 20.6 mL/gVS, respectively. Biomethane generation followed a similar trend with 78.9 ± 18.5, 136.24 ± 8.63, 134.7 ± 20.8, 187.14 ± 10.84, 141.5 ± 31.0, 128.3 ± 16.0, and

140.39 ± 10.17 mL/gVS methane yield from 100:0, 90:10, 70:30, 50:50, 30:70, 10:90, and 0:100 ratios of CD and MC, respectively. Shah and Tabassum [61] found 136.8 mL/gVS methane yield from chemically pretreated maize cob, which was slightly lower than the gas yield (Figure 4b) from this experiment. Difference in gas production might be due to source of waste and type of pretreatment used for maize cob before using it as feedstock for anaerobic digestion. Methane yield from mono-digestion of CD was comparatively lower than the results Li et al. [62] found during anaerobic digestion of cow dung (146 mL/gVS), and the difference in biogas yield might be due to difference in feedstock property of cattle, characteristics of CD used, and method of anaerobic digestion. The highest biogas and methane production (Figure 4a,b) was found at 50:50 ratio of CD and MC. This might be due to the optimum pH (7.32), TS (9.2%), and C/N ratio of feedstock. Kelly [63] reported that 10% total solid in feedstock is best suited for wet anaerobic digestion. Biogas production was 138.05% and 32.02% higher than mono-digestion of CD and MC, respectively. Methane yields also showed 137.18% and 33.30% higher increments than digestion of CD and MC alone. Biogas production from all other test groups (90:10, 70:30, 30:70, and 10:90) also increased with time but not as much as 50:50 ratio. This might be due to higher degradation of volatile solid (Tables 1 and 2) and higher positive synergy of 50:50 ratio during anaerobic digestion. Khatun et al. [24] also reported maximum biomethane potential at 50:50 ratio of banana peel and poultry droppings due to optimum process parameters and positive synergy of co-digestion. Biogas production at 50:50 ratio was 2.38, 1.37, 0.137, 1.29, 1.45, and 1.32 times higher than 100:0, 90:10, 70:30, 30:70, 10:90, and 0:100 ratios of CD and MC, respectively.

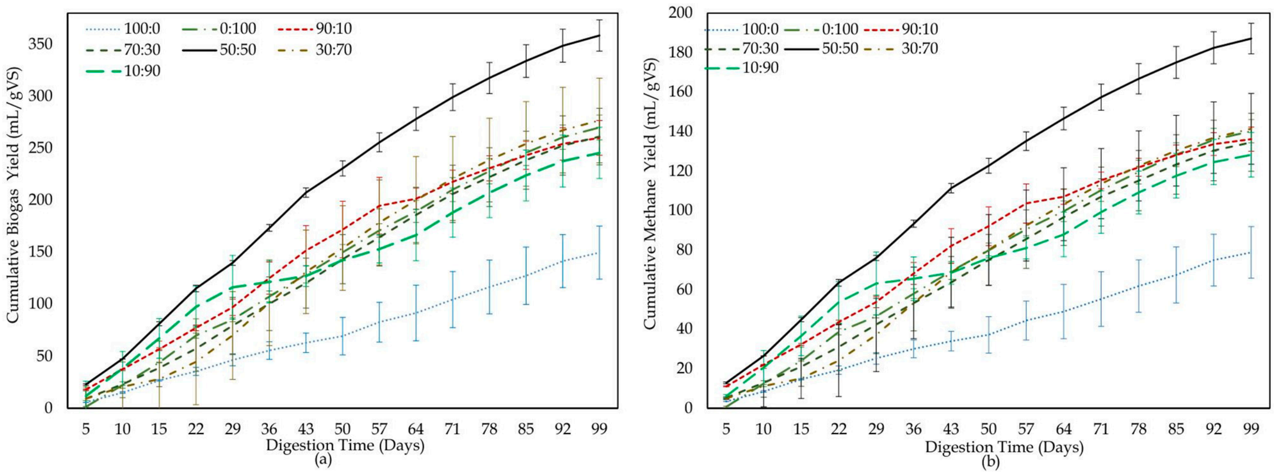

Figure 4. Cumulative (**a**) biogas and (**b**) methane yield during ACoD of CD and MC.

3.5. Prediction of ACoD of CD and MC from Kinetic Modeling

Kinetic analysis of biogas yield ensures the accuracy of data from the anaerobic digestion process [18]. Predicted kinetics parameters based on total methane yield during 99 days of digestion time are listed in Table 3. All four kinetic models showed the coefficient of correlation value (R^2) for model fitting was greater than 0.9. But, the predicted methane yield of the first-order model did not follow the similar trend of the methane yield in the cases of 100:0 (Figure 5a), 70:30 (Figure 5c), and 30:70 (Figure 5e), and the value of R^2 was also lower for all test groups than the other models. So, this was not the best-suited model for predicting the ACoD process. Cone model fitting for 100:0, 90:10, 70:30, 50:50, 30:70, 10:90, and 0:100 resulted in maximum biomethane production (B_o), and they were 153.39%, 36.66%, 78.17%, 41.81%, 205.02%, 84.74%, and 24.67% higher than the experimental yield, respectively (Table 3 and Figure 4b). Such a huge difference makes it difficult to forecast accurate biomethane generation and resulted in invalid parameters. Both the modified Gompertz models and Logistic model showed that lag phase reduced during co-digestion of CD and MC at 50:50 ratio, which indicates faster degradation during ACoD. The addition of substrates at proper ratio reduces lag phase due to nutrient balancing and active microbial growth. Li et al. [18] found that using additives at proper percentages reduced the lag phase for ACoD systems. Although the R^2 values of the modified Gompertz model and Logistic model were almost the same and the RMSE of the modified Gompertz model was slightly lower, the modified Gompertz model showed 42.53%, 4.59%, 15.33%, 4.78%, 10.82%, 13.31%, and 13.25% deviations (for predicted methane yield) from experimental methane yield for 100:0, 90:10, 70:30, 50:50, 30:70, 10:90, and 0:100 test groups of CD and MC, respectively. This model was also not accurate enough, as Raposo et al. [64] reported a deviation greater than 10% that indicated the invalidation of proposed model. The Logistic model showed comparatively better performance with higher R^2 (>0.93) and lower difference between predicted and experimental methane yield (<10%), with an exception for mono-digestion of CD alone. However, this result was contradicted with Wang et al. [47], where they reported a lower deviation of predicted and experimental yield using the modified Gompertz model compared to the logistic model (2.1–5.3%) in the case of anaerobic digestion of cattle manure adding binary and ternary trace elements. This contradiction might be due to the type of substrate and trend of biomethane production. Both the modified Gompertz model and logistic model revealed that the time required for initialization of methanization (λ) during co-digestion was lower than mono-digestion, except for the 30:70 ratio, which might be due to the antagonistic effect of mixing substrate at this ratio and process instability. Therefore, among these four models, the logistic model should be used to predict biomethane production from anaerobic co-digestion.

Table 3. Parameters from different kinetic modeling.

Name of Kinetic Model	Parameters	100:0	90:10	70:30	50:50	30:70	10:90	0:100
First-Order Model	B_o	100.00	229.00	200.10	316.50	177.80	195.50	602.40
	K	0.01	0.01	0.01	0.01	0.01	0.01	0.00
	R^2	0.94	0.97	0.96	0.98	0.93	0.96	0.99
	RMSE	6.42	7.79	9.33	9.94	13.66	8.49	5.25
Cone Model	B_o	200.00	186.20	239.90	265.40	198.60	391.40	259.20
	K	0.01	0.02	0.01	0.02	0.02	0.01	0.01
	n	1.31	1.54	1.52	1.47	1.92	0.94	1.42
	R^2	0.98	0.98	0.99	0.98	0.99	0.96	0.99
	RMSE	3.53	6.84	3.96	8.85	2.63	8.70	4.02
Modified Gompertz Model	B_o	112.50	142.50	155.30	196.10	156.80	145.40	158.90
	R_{max}	0.90	2.09	1.83	2.79	2.12	1.50	1.89
	λ	6.85	3.92	8.37	3.45	11.87	−3.53	6.76
	R^2	0.98	0.98	0.99	0.98	0.99	0.94	0.99
	RMSE	3.74	6.84	4.36	9.45	2.64	10.07	5.25
Logistic Model	B_o	90.26	133.60	138.30	183.90	141.60	134.70	143.10
	R_{max}	0.97	2.15	1.96	2.84	2.29	1.49	1.99
	λ	11.11	6.04	11.99	5.33	15.40	−2.22	10.02
	R^2	0.98	0.98	0.99	0.97	0.99	0.93	0.98
	RMSE	4.28	7.71	5.66	11.04	4.55	11.03	6.92

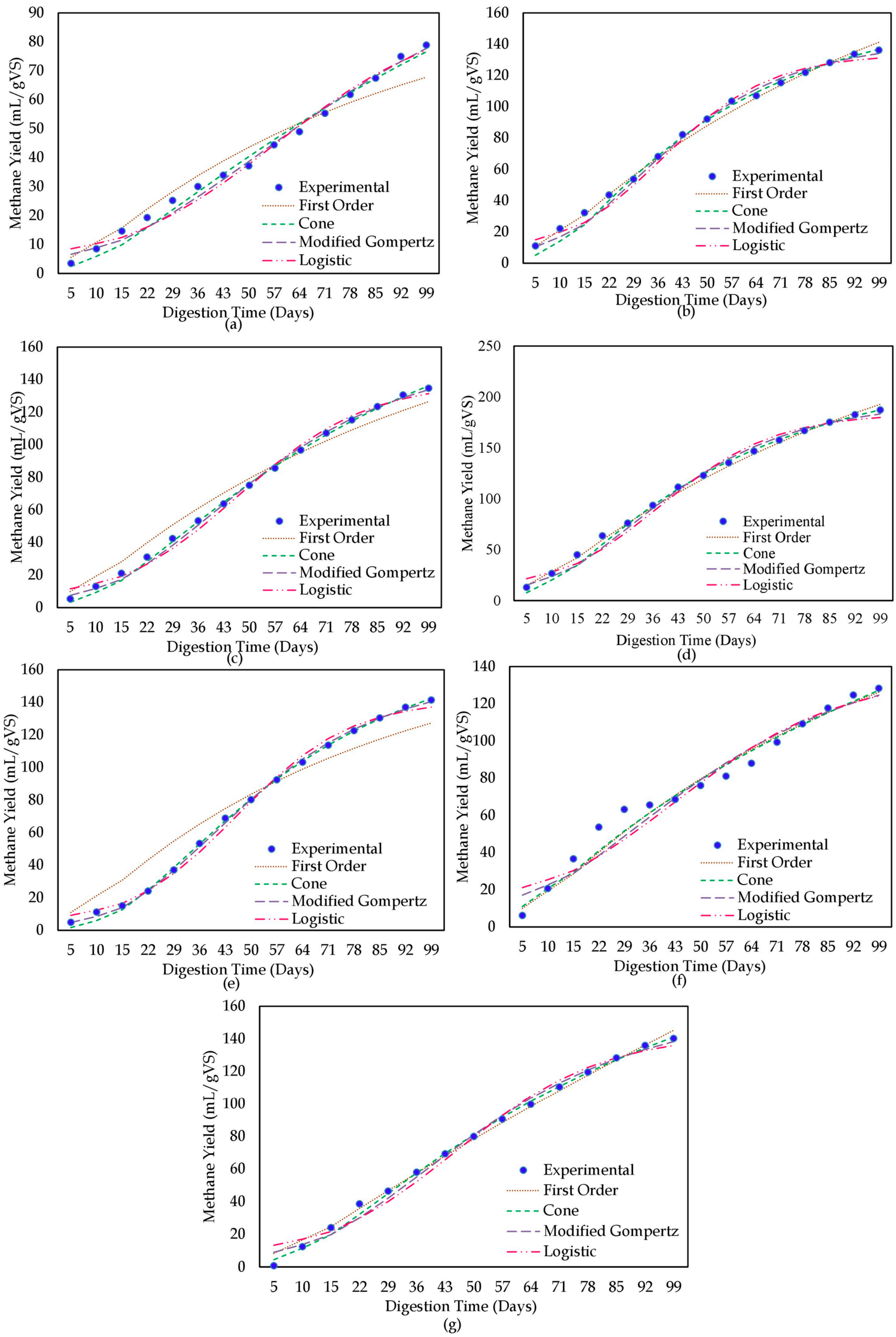

Figure 5. Plots of measured and predicted cumulative methane yields of CD:MC: (**a**) 100:0, (**b**) 90:10, (**c**) 70:30, (**d**) 50:50, (**e**) 30:70, (**f**) 10:90, and (**g**) 0:100.

3.6. Nutrient Increments of Digestate from ACoD

N, P, and K contents of feedstock and digestate are shown in Figure 6a, Figure 6b, and Figure 6c, respectively. N content was increased for all test groups after digestion (Figure 5a). The 50:50 ratio has the highest increment of N, which might be due to improved mineralization of organic matter. N content of 50:50 ratio was found to be 1.746% after digestion, and according to Abbas et al. [15], the N content of soil and fertilizer were 0.5% and 1.71%, respectively. So, digestate of ACoD at 50:50 ratio of CD and MC can be used in nitrogen-deficit soil. According to Wang et al. [47], AD of substrates increases nutrient content of fertilizer such as N, P, and K. The P content of all test groups increased after digestion, except for the 100:0 ratio, which might be due to nutrient imbalance as it was mono-digestion of CD. Möller and Müller [65] also reported that manure digestion has a negative influence on P content availability to plant. As cow dung was mixed with maize cob at a 50:50 ratio, that is why an increment in P content was also lower in this ratio compared to MC alone. The K content was increased for CD and MC alone but there was no significant change in the 50:50 ratio of CD and MC after digestion. This might be due to microbial activity. Total nutrient content (NPK) after 99 days digestion of different test groups is illustrated in Figure 7. Total nutrient content after digestion did not show significant differences during co-digestion. This result might be contradictory with Abbas et al. [15], who found that co-digestion of cow manure with food waste increased nutrient content after digestion when compared to mono-digestion. This difference in results might be due to the type of co-substrates, as Edith et al. [66] also did not find significant difference in P and K contents between digestate of urine with manioc effluent and digestate of mixture of urine and cow dung with manioc effluent. This batch study showed percent increments of total nutrient after the digestion 100:0, 50:50, and 0:100 ratios were 14.39%, 21.12%, and 15.20%, respectively, compared to feedstock (Figure 6). This implies that anaerobic co-digestion can not only enhance the biogas production but can also produce nitrogen-enriched digestate, which can be used in nitrogen-deficit soil. Further enhancement of digestate quality is also possible with the addition of suitable additives including composite [67], vermiculite [68], bio-based carbon [69], and different salts of iron [70].

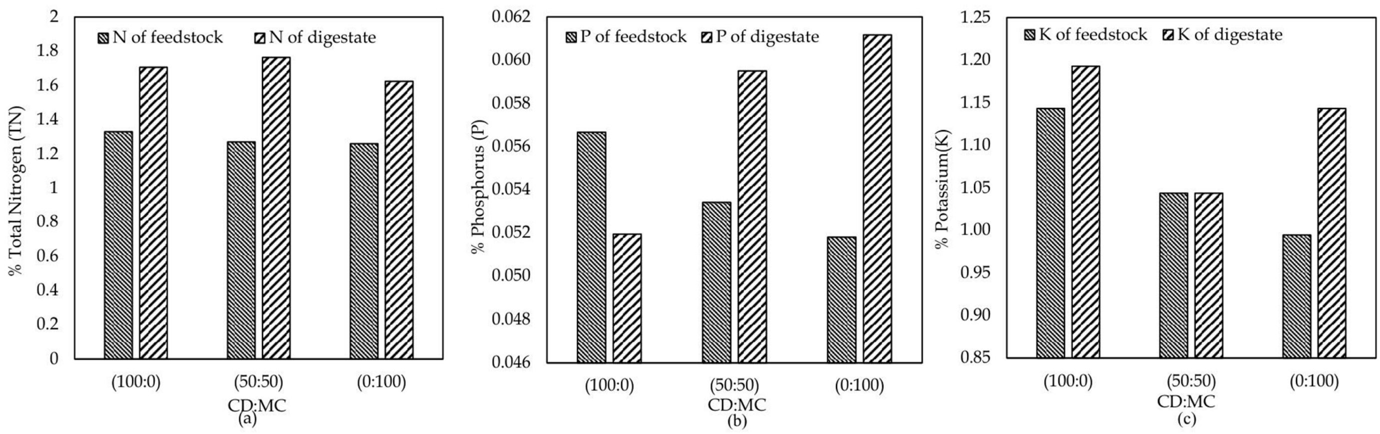

Figure 6. Nutrient contents of feedstock and digestate of (**a**) N, (**b**) P, and (**c**) K.

3.7. Circular Bio-Economy and Anaerobic Co-Digestion of CD and MC

Contribution of biogas and digestate produced from anaerobic co-digestion of cow dung and maize cob at optimum ratio (50:50 of CD and MC) is demonstrated in Figure 8 based on the biogas and digestate production in this batch study. Every year, use of maize cob waste and cow dung for anaerobic co-digestion could produce a high volume of biogas. Full-scale use of maize cob produced in Bangladesh with abundant cow dung produced around 3.23×10^8 m^3 biogas annually (Figure 8). Among various uses, this biogas could be converted into 3.15×10^6 GJ heat and 716.63 GWh electricity using CHP

(Combined Heat and Electricity) (Figure 8). Such vast amounts of heat could be used for heating animal farms, drying grain and storage of food product maintaining optimum temperature, and such use of heat would reduce cost of extra heat generation and may contribute to the national energy security of the country. Electricity produced from biogas may also contribute to the electricity supply chain reducing the dependence on fossil fuel sources. During co-digestion, along with biogas, around 1.00 × 10^9 kg solid digestates are produced annually, which contain 176.74 × 10^4, 5.96 × 10^4, and 104.57 × 10^4 kg nitrogen phosphorus, and potassium, respectively (Figure 8). Proper use of digestate might also reduce production and use of organic fertilizer. Use of digestate as fertilizer and electricity produced from biogas for animal farming and other purposes might decrease both crop and livestock production cost, which would ultimately define circular bio-economy with zero waste generation, as waste was converted into energy and organic fertilizer.

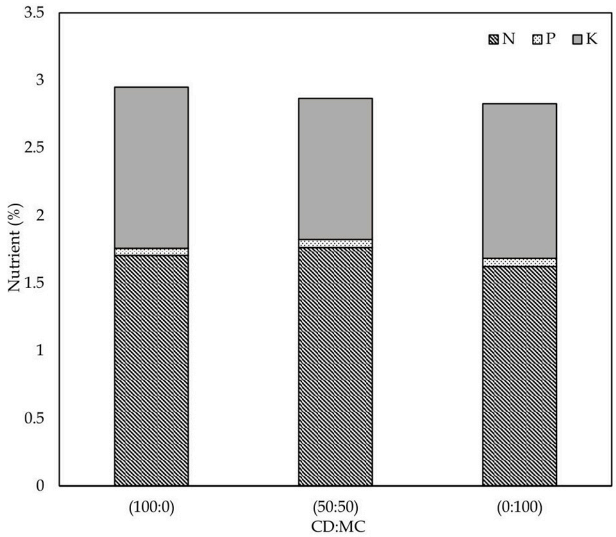

Figure 7. Total nutrient content after digestion at different mixing ratios of CD and MC.

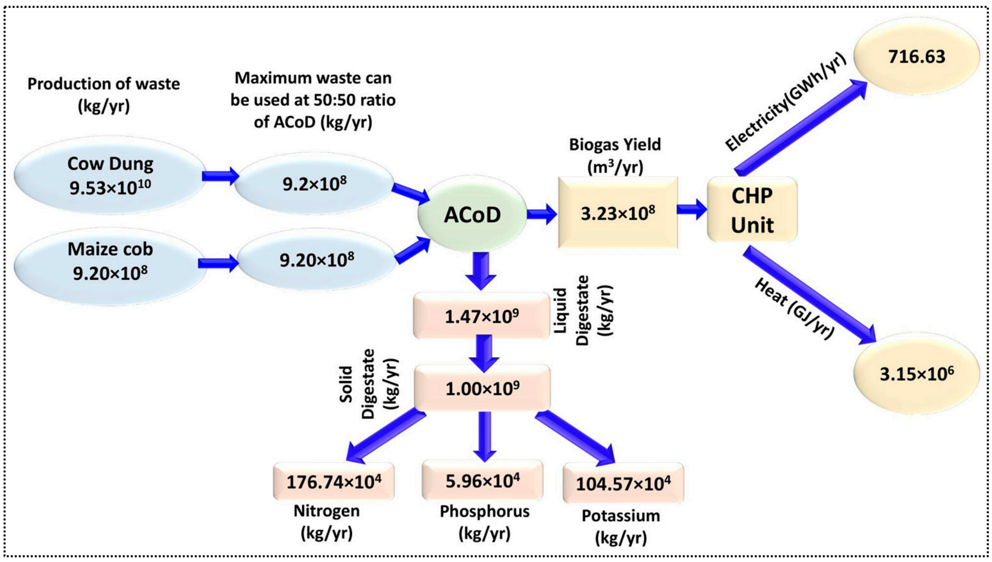

Figure 8. Energy and nutrient production from optimum ratio of CD and MC.

3.8. SWOT Analysis of Anaerobic Co-Digestion of CD and MC

SWOT analysis is a structured method to develop strategy of an organization to achieve its objectives considering all the factors affecting the system including strength, weakness, opportunity, and threats to achieve the goal [71]. So, SWOT analysis results of the anaerobic digestion system showed the possibility and future of implementing this system in field levels with probable risk and benefits. SWOT analysis results of ACoD of CD and MC for circular economy are demonstrated in Figure 9. Abundant production of CD and MC per year [3] was considered as the main motivation along with management of vast amounts of waste to reduce greenhouse gas emissions. Major strengths included implementation of circular bio-economy through contributing renewable energy sources by maximizing gas production (Figure 4) and providing nutrient-enriched fertilizer (Figures 7 and 8). Weaknesses of ACoD of CD and MC included construction of plant, as Nsair et al. [72] reported biogas plant design considers type of substrate used as feedstock, mixing type, dry matter content, and organic loading rate. Pretreatment of substrates is another weakness of ACoD, as in this experiment, mechanical pretreatment of MC was required for faster degradation, which involves energy requirement for large-scale digestion plant. In fact, longer retention time is also required in the case of lignocellulosic waste (up to 99 days were required in this study). But, there will be a difference in all of these factors in the case of construction of a plant for ACoD instead of AD. Until now, dominance of fossil fuel is observed in Bangladesh, and Saha et al. [73] reported AD of animal manure is practiced. So, creating awareness for implementing ACoD technology at the field level is also a great threat. Moreover, the collection issue due to the segregated generation of waste over the whole country poses a threat to the successful implementation of the ACoD system. In fact, waste collection from different areas also increases the cost involved in the ACoD process. In this experiment MC was collected from Jamalpur, Bangladesh, where incineration is the traditional practice. So, incineration of MC is also a threat.

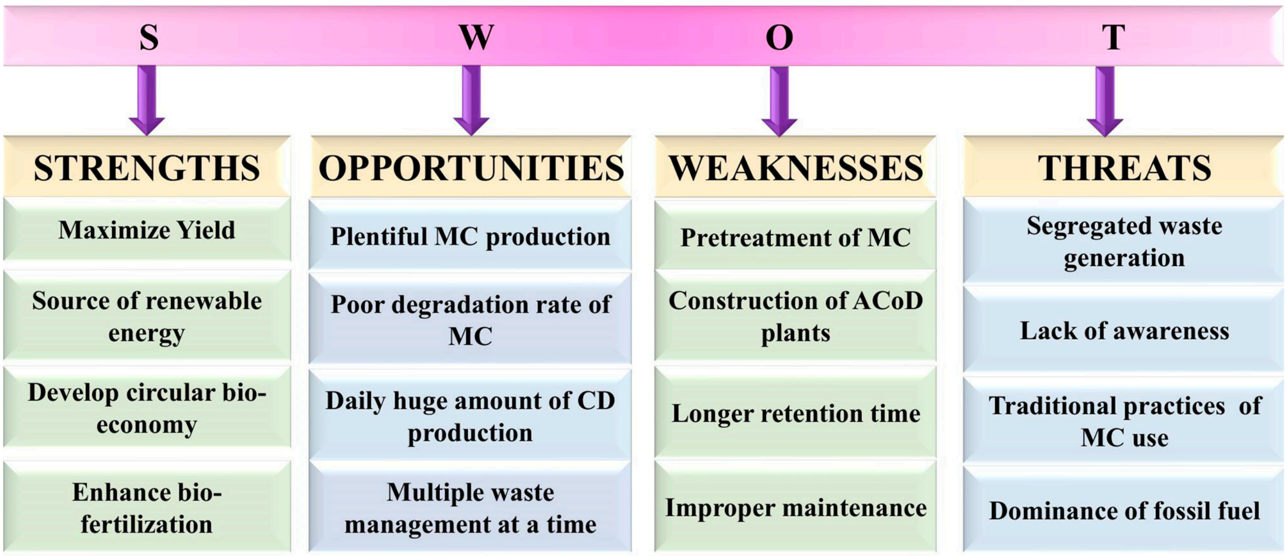

Figure 9. SWOT analysis of using ACoD of CD and MC for circular bio-economy.

4. Conclusions

Production of gigantic agricultural waste causes faster proliferation of pollution. This batch assay on ACoD of CD and MC resulted in better gas yield in co-digestion compared to mono-digestion of substrates. Biogas production at a 50:50 ratio resulted in maximum gas yield for optimum process parameters and synergy. Kinetic modeling showed lag phase was reduced during co-digestion at a 50:50 ratio, and the logistic model was best suited with higher R^2 and lower deviation between predicted and estimated biogas yield. Biogas production from co-digestion of CD with annually produced MC could result in a great contribution to electricity generation and heat production, which can be used in various sectors for human livelihood and animal farming. Digestate produced from 50:50 ratio had no significant difference than the other ratios, but its nutrient increment efficiency was higher than mono-digestion, which promoted the co-digestion at this ration. Percentage nitrogen increment was also high during co-digestion, which indicated use of digestate in nitrogen-deficit soil. Such a system of waste management may contribute in the establishment of circular bio-economy with production of renewable energy and fertilizer by converting waste to energy. Hence, co-digestion not only increased biogas production but also produced nutrient-enriched fertilizer, representing the circular bio-economic model. These results will also help policy makers in implementing the circular bio-economic model worldwide. Further research on pretreatment of maize cob may help to enhance biomethane production, and the use of biogas and digestate as fertilizer in the field will provide an idea about the extent of implementation of the circular economic system.

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