Bioresource Technology Reports 29 (2025) 102013

Contents lists available at ScienceDirect

Bioresource Technology Reports

journal homepage: www.sciencedirect.com/journal/bioresource-technology-reports

Enhancement of biomethane yield rate in anaerobic co-digestion of cattle dung and untreated vegetable waste through the amendment of water-hyacinth biochar

Shayaram Basumatary [a], Harrison Hihu Muigai [b], Pranab Goswami [c], Pankaj Kalita [a,*]

[a] School of Energy Science and Engineering, Indian Institute of Technology Guwahati, 781039, India
[b] Department of Agricultural Engineering & Energy Technology, Jaramogi Oginga Odinga University of Science and Technology, Bondo, Kenya
[c] Department of Biosciences and Bioengineering, Indian Institute of Technology Guwahati, 781039, India

ARTICLE INFO

Keywords:
Biochemical methane potential
Biochar
Co-substrate mixing ratio
Modified Gompertz model

ABSTRACT

This study investigates the effect of biochar (BC) amendment on the anaerobic co-digestion (AcoD) of cattle dung (CD) and untreated vegetable waste (VW) performed at different co-substrates mixing ratios (CMR) of 70:30, 60:40, 50:50, 40:60, and 30:70 under ambient and mesophilic conditions. The mesophilic BC-added digester with a CMR of 60:40 exhibited 13.19 % and 39.26 % higher cumulative methane yield (CMY) than the corresponding uncontrolled digesters (CMR 60:40) with and without BC-added over 45 days of experiments. Subsequently, considering CMR 60:40, another group of biochemical methane potential experiments was conducted at ambient conditions, incorporating varying amounts of BC, viz. 5, 10, 15, 20, and 25 gL^{-1}. The digester comprising 15 gL^{-1} BC achieved the highest CMY, recommending it as the optimal amount of BC addition for the AcoD of CD and VW. This study discloses that BC addition is a significant approach to increasing CH_4 yield.

1. Introduction

Open dumping of biodegradable waste, such as cattle dung (CD) and vegetable waste (VW), significantly impacts the environment. It contaminates soil and water through leachate generation and contributes to air pollution by releasing hazardous gases (Ren et al., 2018). The primary greenhouse gases (GHG) released from CD and VW are carbon dioxide (CO_2), methane (CH_4), dinitrogen oxide and fluorinated compounds, contributing to weather change. US Environmental Protection Agency reported worldwide food waste shares around 8 % of anthropogenic GHGs (U.S. EPA, 2021). Likewise, the livestock share roughly 18 % of GHGs globally. Further, livestock is responsible for the generations of agricultural CH_4 (80 %) and anthropogenic CH_4 (35 %,) which is equivalent to 2.2 billion tons of CO_2 (Sejian et al., 2016). In this regard, the United Nations (UN) takes various steps to reduce global warming. UN Climate Change Conference (COP21) held in Paris, France, aims to put efforts to limit warming to 1.5 °C above pre-industrial levels, and substantial emission reductions must be accomplished worldwide by 2030 (COP28, 2023).

Among the several approaches for lowering emissions, anaerobic digestion (AD) can also be recognised as an appropriate and adaptable technology for treating biodegradable waste products and harnessing renewable energy. It also offers a cost-effective and sustainable solution for lowering emissions. The AD process produces biogas via microorganisms in an oxygen-free environment. However, microbial activities and growth are influenced by many factors, such as the substrates' degradability, temperature, alkalinity, and mineral concentrations (Basumatary et al., 2024). Moreover, biogas generation relies on feedstocks' total solid (TSC) and volatile solid (VSC) contents. Thus, preparing the slurry within the desired range is essential to achieve a higher biogas yield. Additionally, blending additive materials has vital benefits for improving the AD system.

Various investigators studied the impact of biochar (BC) incorporation on AD of organic waste. BC is a carbon-rich material produced by pyrolysing, gasifying, or hydrothermal carbonising biomass without oxygen (Ighalo et al., 2023). Earlier studies reported that blending BC with anaerobic substrates improves the performance of the AD process. Adding an optimum quantity of BC increases the CH_4 generation rate, enhances operational stability, accelerates the evolution of anaerobic bacteria, immobilises microorganisms, and improves biogas quality (Chen et al., 2023; Zhao et al., 2021). The key benefits realised in the AD system demonstrate that BC possesses robust physical and chemical

---

* Corresponding author.
E-mail address: pankajk@iitg.ac.in (P. Kalita).

https://doi.org/10.1016/j.biteb.2024.102013
Received 8 October 2024; Received in revised form 7 December 2024; Accepted 18 December 2024

Table 1
Experimental design for co-digestion.

Co-substrate mixing ratio	CD: VW (m/m[a]) (i)	CD (g) (ii)	VW (g) (iii)	Water (g) (iv)	Total (g) (v) = Σ (ii) + (iii) + (iv)
CMR 70:30	70:30	245	105	350	700
CMR 60:40	60:40	210	140	350	700
CMR 50:50	50:50	175	175	350	700
CMR 40:60	40:60	140	210	350	700
CMR 30:70	30:70	105	245	350	700

[a] m/m stands for mass by mass basis, g stands for gram.

properties that enhance the AD process. Recent studies have reported that BC is a highly porous material that provides colonisation space for microorganisms (Li et al., 2022). Additionally, several functional groups, alkaline elements, and interspecies electron exchange capacity of BC boost the biogas generation in the anaerobic co-digestion (AcoD) process (Kumar et al., 2021). The BC can mitigate the generation of ammonia and volatile fatty acids, preventing AcoD failure (Sun et al., 2019). The performance of AcoD with BC is influenced not only by the physico-chemical properties of BC but also by the types of substrates and their mixing ratio.

Even though numerous studies have examined the AcoD of CD and untreated VW, there is limited literature on the viability of adding water hyacinth biochar (WHBC) in the co-digestion, particularly with varying CD and VW mixing ratios. The BC derived from various feedstocks may significantly differ in its effectiveness in enhancing AD performance. As water hyacinth is available in the North-East India, this substrate is considered for the preparation of BC in the present study. Compared with other BC prepared from available biomass such as tree leaves (Sahota et al., 2018), citrus peel BC (Jiang et al., 2020) and chicken manure (Pan et al., 2019), WHBC was found to have a higher surface area and pore size. The low hydrogen/carbon (H/C) ratio in the WHBC could be a favourable property to enhance CH_4 production upon its addition to AcoD. Furthermore, a highly alkaline nature of WHBC indicates its hydrophobicity and is a desirable property of adsorption capacity to mitigate inhibition and attract microbes to the BC surface. Thus, use of WHBC in the AcoD will be beneficial. This study conducted laboratory-scale AcoD experiments using the different co-substrate mixing ratios (CMR) of CD and untreated VW with and without the blending of WHBC. The primary goals of the current investigations are (i) to identify the optimal CMR for AcoD of CD and VW, (ii) to study the effect of WHBC incorporation on AcoD of CD and VW, and (iii) to evaluate the most appropriate amount of WHBC to be added for maximising CH_4 production. Further, a prediction of the CH_4 generation potential was executed using a modified Gompertz model. The impact of operating parameters, including pH value and temperature, on CH_4 generation rate was also studied.

2. Materials and methods

2.1. *Feedstock collection, preparation and characterisation*

The feedstocks employed in AcoD were CD and VW. The VW was obtained from the dining hall of a hostel at IIT Guwahati, India. The main components of untreated VW were green mustard leaves, eggplants, potatoes, cabbages, long gourds, radish leaves, and other vegetables. Before being introduced into the digester for AcoD, the VW was ground using a mixer grinder (Bajaj Model: GX 8750 W) and stored at a temperature of 4 °C. The CD was gathered from a farm near the institute. Fresh WH was obtained from the IIT Guwahati campus and cleaned with water before being chopped into small pieces (about 3 mm). After natural drying for 5–6 days, it was put in an oven (Optics Technology, India) for 24 h at 105 ± 2 °C to eliminate wetness. Subsequently, BC was prepared through a pyrolyser (Das and Co., India) at 550 °C, setting the heating rate at 10 °C min^{-1} for 1 h by supplying argon gas to make the reactor oxygen-free (Basumatary et al., 2024). Before being added to digesters, the WHBC was ground using a mixer grinder until it could pass through a mesh size sieve of 100 μm.

The MC, TSC and VSC of substrates were evaluated employing the standard methods reported by APHA (2017). The ultimate analysis of

Table 3
Physico-chemical properties of WHBC.

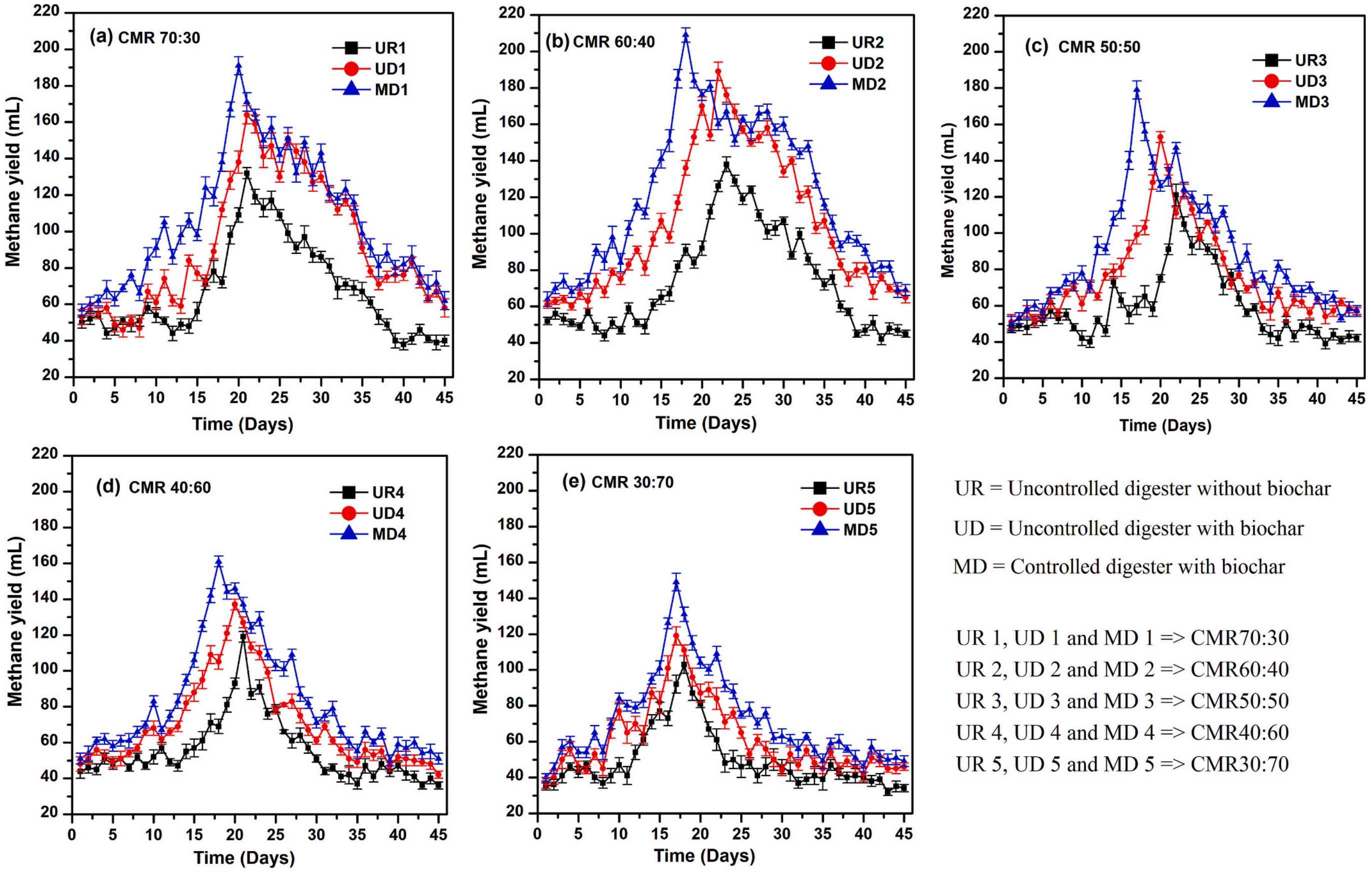
Investigation	Parameter	Unit	Value
Proximate analysis	MC	%	3.82 ± 0.43
	AC	%	19.59 ± 0.27
	VM	%	13.64 ± 0.14
	FC	%	62.96 ± 0.05
CHNSO study	C	wt%	41.35 ± 0.11
	H	wt%	1.67 ± 0.08
	N	wt%	3.34 ± 0.06
	S	wt%	0.52 ± 0.03
	O	wt%	53.11 ± 0.10
	H/C	–	0.04 ± 0.00
	O/C	–	1.28 ± 0.03
AAE metals	K	wt%	9.47 ± 0.02
	Ca	wt%	5.73 ± 0.09
	Na	wt%	1.41 ± 0.07
	Mg	wt%	1.11 ± 0.08
Others elements	P	wt%	3.12 ± 0.09
	Cl	wt%	5.23 ± 0.10
Physisorption isotherm	S_{BET}	m^2/g	14.10 ± 0.11
	V_p	cm^3/g	0.05 ± 0.01
	d_p	nm	11.94 ± 0.05
Others analysis	pH	–	10.07 ± 0.06
	EC	dS/m	33.28 ± 0.85

Table 4
Functional group of FT-IR analysis for WHBC.

Bond	Functional group	Frequency from this study (cm^{-1})	Frequency from the literature (cm^{-1})	Reference
O—H	Alcohol, phenol	3610	3650–3600	NIU (2023)
C=C	Alkene, aromatic	1409	1700–1400	Shen et al. (2015)
C—O	Alcohol	1037	1200–1000	Domingues et al. (2017)
C—H	Aromatic	874	900–690	Shen et al. (2015)
C—H	Aliphatic, aromatic	562	–	Shen et al. (2015)

Table 2
Characterisation of co-substrates and their slurries.

Parameters	Raw CD	Raw VW	Co-substrates mixing ratio				
			CMR 70:30	CMR 60:40	CMR 50:50	CMR 40:60	CMR 30:70
MC (%)	84.08 ± 0.26	91.65 ± 0.02	91.77 ± 0.09	92.14 ± 0.07	92.86 ± 0.04	93.31 ± 0.10	94.21 ± 0.15
TS (%)	15.92 ± 0.17	8.37 ± 0.02	8.23 ± 0.09	7.86 ± 0.06	7.14 ± 0.04	6.69 ± 0.09	5.79 ± 0.15
VS (%TS)	83.50 ± 0.10	94.25 ± 0.14	74.70 ± 0.17	75.93 ± 0.11	77.00 ± 0.03	81.06 ± 0.05	83.32 ± 0.06
C/N ratio	25.82 ± 1.10	18.75 ± 0.29	22.81 ± 0.13	21.92 ± 1.02	21.26 ± 0.54	20.52 ± 1.06	19.14 ± 0.25
pH	6.39 ± 0.09	4.31 ± 0.05	5.98 ± 0.09	5.76 ± 0.10	5.21 ± 0.08	5.03 ± 0.06	4.66 ± 0.05



UR = Uncontrolled digester without biochar

UD = Uncontrolled digester with biochar

MD = Controlled digester with biochar

UR 1, UD 1 and MD 1 => CMR70:30
UR 2, UD 2 and MD 2 => CMR60:40
UR 3, UD 3 and MD 3 => CMR50:50
UR 4, UD 4 and MD 4 => CMR40:60
UR 5, UD 5 and MD 5 => CMR30:70

Fig. 1. Daily CH_4 yield from the digesters with CMRs of (a) 70:30, (b) 60:40, (c) 50:50, (d) 40:60, and (e) 30:70.

the substrates and BC was performed according to ASTM: D5373-16 using a CHNSO analyser (Euro EA, Italy). The proximate analysis of BC was performed using ASTM methods viz. E871-82, D1102-84, and E872-82 to evaluate MC, ash content (AC), and volatile matter (Basumatary et al., 2024). The fixed carbon (FC) was assessed by calculating the weight difference. The morphological and microstructure of BC were inspected by a scanning electron microscope (SEM) (Zeiss, Germany). The BET surface area (S_{BET}), pore size (d_p), and pore volume (V_p) of BC were analysed with a Brunauer–Emmet–Teller (BET) analyser (Quantachrome Instruments, USA). The BC was degassed for 5 h at 200 °C prior to analysis. To assess the presence of mineral matters such as alkali and alkaline earth (AAE) elements in biochar, energy-dispersive X-ray spectroscopy (EDX) (Zeiss, Germany) was employed. The X-ray diffractometer (XRD) (Rigaku Technologies, Japan) was used to identify the crystalline compounds of BC. The scanning range (2θ) was set between 10° to 70° with a scanning rate of 15°/min. Further, the surface functional groups of BC samples were assessed by a Fourier transform infrared (FT-IR) spectrometer (PerkinElmer, Singapore, Model: Spectrum two) in the 4000–400 cm^{-1} wave range. The alkalinity level of WHBC was measured by referring to methods illustrated by Liu et al. (2022) using a pH analyser.

2.2. Biochemical methane potential (BMP) experimental set up

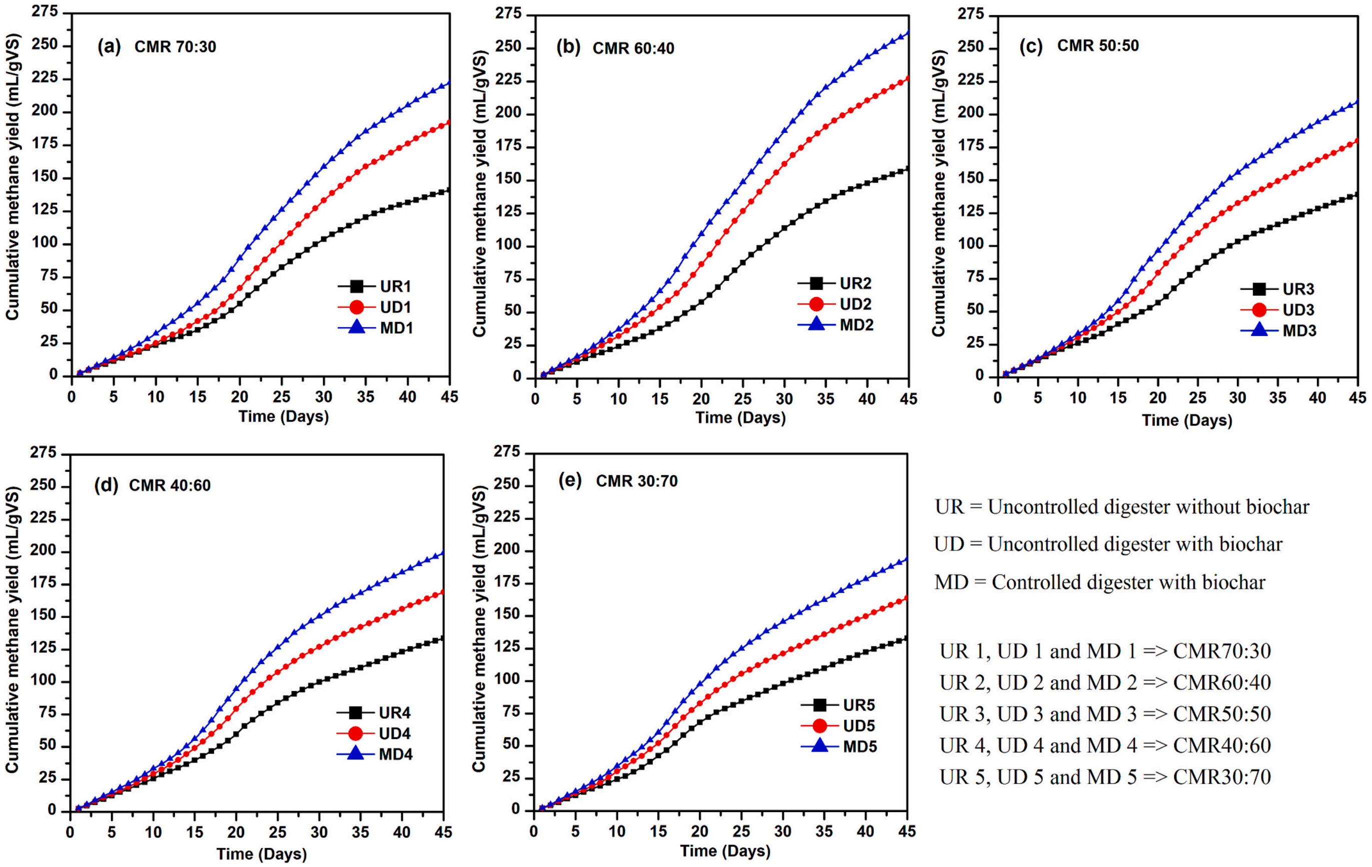
Initially, three sets of BMP tests were conducted at different CMRs of CD: VW, such as 70:30, 60:40, 50:50, 40:60, and 30:70 on a wet mass basis parallelly in triplicate, as depicted in Table 1. The objective of selecting the different CMRs was to determine the optimal CMR for achieving the highest methane yield. The BMP test was performed according to the methodology outlined by Basumatary et al. (2024). The schematic diagram and photograph of BMP tests (Fig. S1) are incorporated in the supplementary materials. The feedstock and distilled water were mixed in a 1:1 ratio. No inoculum was added in the BMP tests, considering CD as the active feedstock. Entire BMP tests were conducted under uncontrolled and controlled temperatures for 45 days. In the set I experiment, no BC was used. However, 10 g of BC, prepared from WH at the pyrolysis temperature of 550 °C, was added arbitrarily to each of the digesters in sets II and III. Additionally, sets I and II experiments were performed at uncontrolled (ambient) temperature, while the temperature of set III was maintained at 37 ± 2 °C using a hot water bath (Equitron Medica, India). Hereafter, considering the best CMR detected in sets I, II and III, another set of the experiment (set IV) was carried out by blending varying quantities of BC (in gL^{-1}): 5, 10, 15, 20, and 25 to recognise the appropriate amount of BC required to be mixed for highest methane production.

2.3. Modified Gompertz model analysis

The CH_4 generation potential from the different CMRs of CD and VW was determined by the modified Gompertz model (MGM) equation. Several researchers have acknowledged the MGM equation as a precise prediction analysis for CH_4 generation potential (Syaichurrozi, 2018; Tian et al., 2020). The MGM equation demonstrates the highest accuracy in predicting cumulative CH_4 yield potential, CH_4 yield rate, and the time required to achieve the highest CH_4 yield compared to other kinetic models. The model parameters were evaluated by curve-fitting the BMP test data (Zhang and Wang, 2021) of Y_C and t using Matlab R2022b, as depicted in Eq. (1).

$$Y_C = Y_P exp\left[-exp\left\{\frac{Y_R.e}{Y_P}(\lambda - t) + 1\right\}\right] \tag{1}$$

where Y_C, Y_P, Y_R, λ and e designate the accumulative specific methane



UR = Uncontrolled digester without biochar
UD = Uncontrolled digester with biochar
MD = Controlled digester with biochar

UR 1, UD 1 and MD 1 => CMR70:30
UR 2, UD 2 and MD 2 => CMR60:40
UR 3, UD 3 and MD 3 => CMR50:50
UR 4, UD 4 and MD 4 => CMR40:60
UR 5, UD 5 and MD 5 => CMR30:70

Fig. 2. Cumulative CH_4 yield from the digesters with CMRs of (a) 70:30, (b) 60:40, (c) 50:50, (d) 40:60, and (e) 30:70.

Table 5
Impact of biochar addition on improving AD performance.

Reference	Substrates	Temperature and HRT of the AD process	Type of biochar	Pyrolysis temperature	Dosage of BC	Performance
Suthar et al. (2022)	CD	35 °C, 35 days	Water hyacinth	350 °C	0.5–1.5 % (v/v)	CH_4 increased by 9.33–19.8 %
Sun et al. (2022)	FW	37 °C, 30 days	Corn straw	600 °C	10 g/L	CMY increased by 22.90 %
Wang et al. (2024)	KW	37 °C, 90 days	Straw digestate	500 °C	15 g/L	CH_4 increased by 20.8 %
Li et al. (2022)	CS and SS (1:1)	36 °C, 30 days	Corn straw	500 °C	10 g/L	CMY increased by 7.96 %,
Kaur et al. (2020)	SS and FW (1:7)	35 °C, 30 days	Wheat straw pellet	550 °C	10 g/L	CMY increased by 24.59 %
This study	CD and VW (60:40)	37 °C, 45 days	Water hyacinth	550 °C	10 g/L	CMY increased by 39.26 %

Where CD: Cattle dung, FW: Food waste, KW: Kitchen waste, CS: Corn straw, SS: Sewage sludge, VW: Vegetable waste, and CMY: Cumulative CH_4 yield.

yield (SMY) at the given time (t) in days (d), highest CH_4 yield potential, highest CH_4 generation rate, lag phase time, and $e = 2.7183$, a constant, respectively.

3. Results and discussions

3.1. Characterisation of substrates and their slurries

Table 2 illustrates the MC, TSC, VSC, and pH values of raw CD, raw VW and their slurries prepared at different CMRs viz. 70:30, 60:40, 50:50, 40:60, and 30:70. Evaluating these parameters is essential to identify the appropriateness of a feedstock for anaerobic digestion, as they extensively impact the performance of the AcoD process and, subsequently, CH_4 production. In this investigation, the MC of CD and VW were 84.08 ± 0.26 % and 91.65 ± 0.02 %, respectively, whereas for the slurries with different CMR, the value of MC ranged from 91.70 % to 94.21 %. A significant amount of MC in the slurry supports microorganisms during the hydrolysis and acidogenesis stages. Insufficient moisture levels can hinder the AD process by promoting acid accumulation (Odejobi et al., 2021; Osei-Owusu et al., 2023). Conversely, higher MC in the feedstock enhances microbial activity in anaerobic digestion (Lay et al., 1997). Previous scientific studies have highlighted the substantial impact of TSC on the AcoD of waste biomass (Indren et al., 2020; Johnravindar et al., 2022). High TSC can inhibit mass transfer between anaerobic bacteria and feedstock, reducing CH_4 generation (Johnravindar et al., 2022). Abbassi-Guendouz et al. (2012) witnessed a higher CH_4 yield rate for TSC of 10 %, which declined as the TSC increased from 10 % to 30 %. In this study, TSC for various CMRs of CD and VW ranged from 5.90 to 8.23 %, while TSC for raw CD and raw VW was 15.90 % and 8.37 %. The TSC of cattle dung was achieved to be consistent with the outcome found by Wang et al. (2022), whereas the TSC for vegetable waste was consistent with the result described by Bouallagui et al. (2009). The VS (% TS) value signifies that the substrates comprising degradable materials can be transformed into biogas. The VS

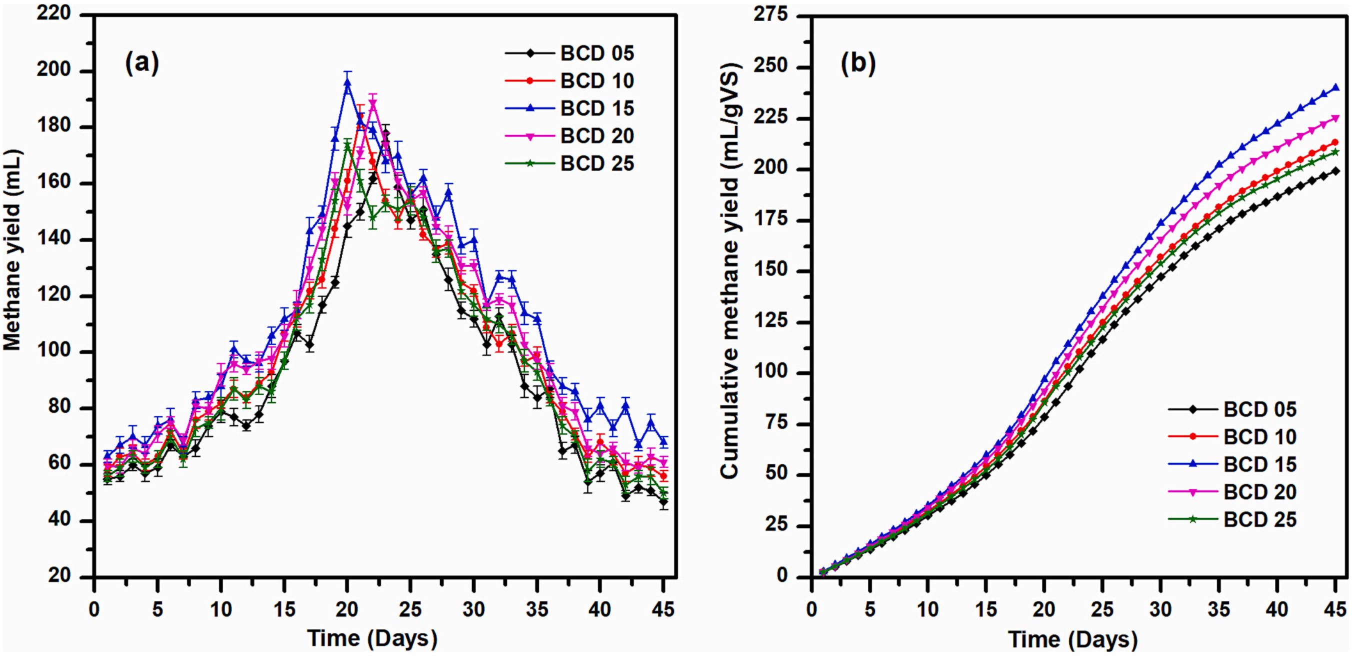


Fig. 3. (a) DMY and (b) CMY from the digesters with the addition of different quantities of BC.

(% TS) value for different CMRs was detected to be 74.70–83.32 %. Further, the pH value of the slurry reduced from 5.98 to 4.66 due to the addition of a higher amount of VW, which was below the desired range. Therefore, improvement of pH value is essential for the growth of microorganisms. This study used biochar prepared from water hyacinth to enhance the pH value. The outcome of BC addition to the AcoD process is elaborated in the following section. The C/N ratio is crucial in determining the level of nutrients for anaerobic bacteria. For the feedstocks with a high C/N ratio, the methanogens consume nitrogen rapidly, which results in lower biogas yield. On the other hand, the feedstocks with an excessively low C/N ratio increase the risk of ammonia inhibition, which is toxic to methanogens and leads to inefficient utilization of carbon sources (Kothari et al., 2014; Mao et al., 2015). Hence, maintaining C/N ratios within the optimal range is essential for achieving higher methane yields. In this study, the C/N ratio for CD and VW were 25.82 ± 1.10 and 18.75 ± 1.07, whereas, for slurry, their values were found in the range of 19.00–23.00 for different mixing ratios. The C/N ratio of the current study was obtained nearly in the optimum range of 20–30, as its value was high for cattle dung. Therefore, the AcoD of co-substrates with low and high C/N ratios can improve anaerobic digestion.

3.2. Results of characterisation of biochar

The physicochemical properties and structures of BC effect the AcoD process (Ovi et al., 2022). Table 3 illustrates the characterisation of BC. The pH level of WHBC was in the alkaline range (10.07 ± 0.06) due to the existence of AC and volatilisation of acidic functional groups (Kumar et al., 2021). The AAE materials (K, Ca, Mg and Na) enhance the alkalinity of co-digestion (Basumatary et al., 2024). Further, some elements like C, N and P assist the growth and metabolism of microbes (Liu et al., 2023). The H/C and O/C values were obtained to be 0.04 ± 0.00 and 1.28 ± 0.03, respectively. These low values of H/C and O/C signify the high hydrophobicity and adsorption capacity of organic pollutants like ammonium (Johnravindar et al., 2022; Xie et al., 2022). The surface textural properties of BC were also analysed. The S_{BET}, V_p and d_p were detected as 14.10 ± 0.11 m^2g^{-1}, 0.05 ± 0.01 cm^3g^{-1}, and 11.94 ± 0.05 nm, respectively. The porosity nature of biochar offers a surface area for the adsorption of carbon dioxide in the AD process (Aramrueang et al., 2022). Further, the SEM image of WHBC (Fig. S2 (a)) signifies biochar's porous structure that provides areas for the colonisation of anaerobic bacteria. The wavelength of FTIR spectra (Fig. S2 (b)) detected is presented in Table 4. These functional groups provide direct interspecies electron transfer (DIET) and raise the progress of microbes in the AcoD system (Shen et al., 2020). The WHBC displays the functional groups, including C—H vibrational groups (aromatic and aliphatic) at 874 and 562 cm^{-1}, stretching vibrations of saturated and unsaturated alcohols C—O at 1037 cm^{-1} and aromatic C═C stretching at 1409 cm^{-1}. Additionally, a low peak at 3610 cm^{-1} in FTIR spectra represents O—H stretching. Besides, XRD spectra (Fig. S2 (c)) detected at various 2-theta (2θ) values confirmed the presence of $CaCO_3$ (29.36°, calcite), $CaSO_4$ (40.98°, 66.76°), KOH (30.86°, 50.37°) and K_2SO_4 (58.76°) which provide buffering effect in AcoD process (Jiang et al., 2020).

3.3. Methane production

The daily and cumulative methane yield at various CMRs, such as 70:30, 60:40, 50:50, 40:60, and 30:70, without and with BC addition under control and uncontrol temperatures are presented in Figs. 1 and 2. The CH_4 production rate was low at the initial phase of the AcoD process. This could be because the oxygen in the reactors restricts the growth of microbes and CH_4 yield at the initial phase of the AD operation (Deepanraj et al., 2017). Subsequently, a high rate of CH_4 yield was observed, likely due to the speedy growth of microbes. Afterwards peak period, CH_4 generation declined. The high peak methane generation was attained between the end of the 2nd and 4th weeks of the AcoD period.

Biochar can enhance biogas generation by improving the microbial environment in the digester. The BC-added digesters conducted at ambient and mesophilic temperatures achieved a higher daily methane yield (DMY) rate compared to the corresponding ambient digesters without BC. The BC-added digesters with CMRs of 70:30, 60:40, 50:50, 40:60, and 30:70 was found to be 26.53, 30.04, 22.62, 20.95, 18.91 % higher volume of cumulative methane yield (CMY) than respective digesters without BC respectively, conducted at ambient temperature, for the HRT of 45 days. Likewise, the BC-added mesophilic digesters generated 36.42, 39.26, 33.47, 32.90 and 31.47 % higher amounts of CMY than the uncontrolled digesters. This study confirms that the AD system can be improved by adding BC. This investigation also concludes

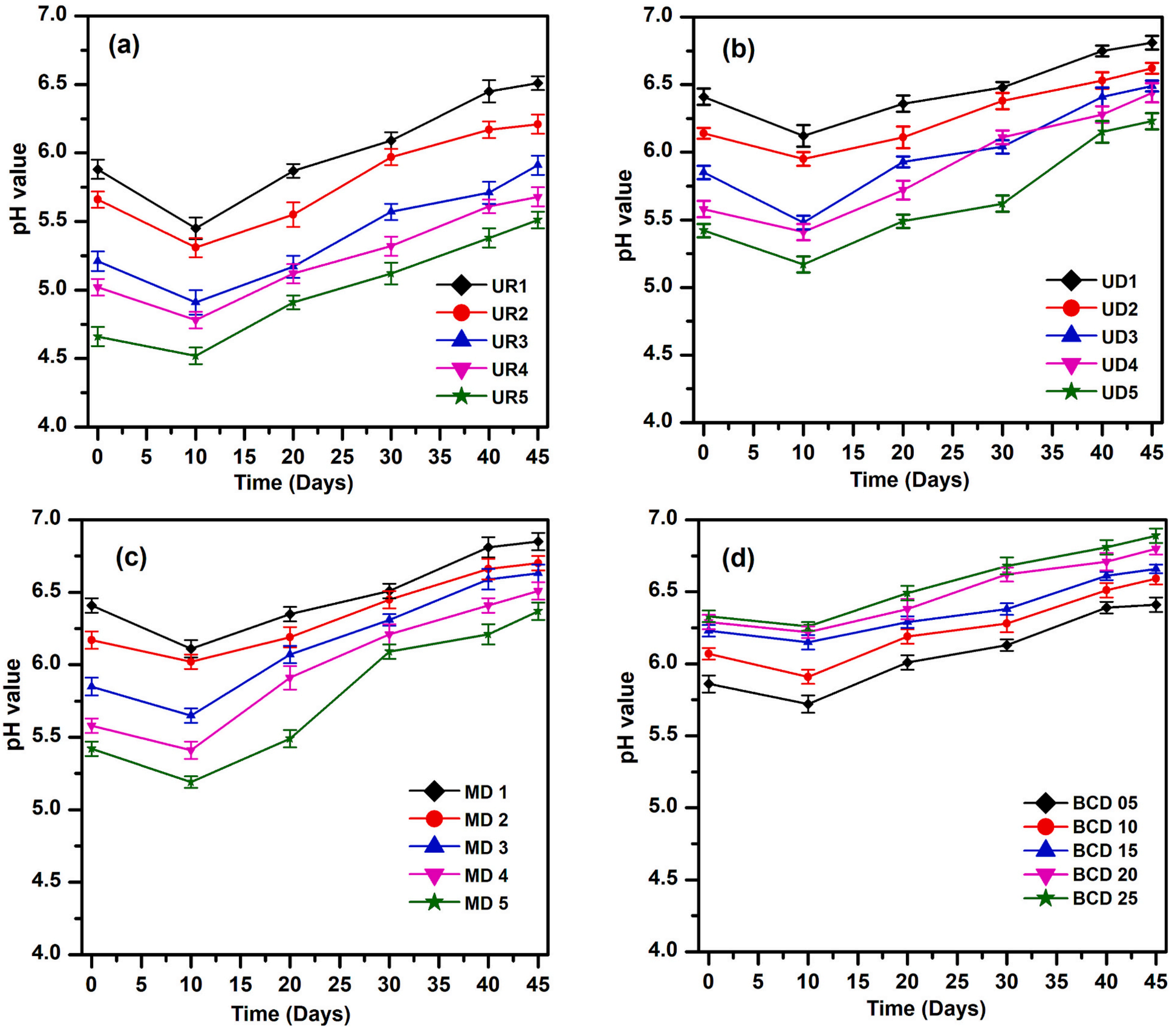


Fig. 4. Variations of pH value for the digesters at (a) ambient temperature without BC, (b) ambient temperature with BC, (c) mesophilic temperature with BC, and (d) ambient temperature with varying amounts of BC for SMR 60:40.

that maintaining the reactor temperature at mesophilic conditions can increase CH_4 generation. A typical comparison between the results of present work and the reported research works is presented in Table 5. This comparative study reveals that the rate of CH_4 generation potential depends on the type of substrates, CMR, types of BC, and pyrolysis temperature of BC. Therefore, analysis of various parameters impacting the methane production rate is essential. Previous studies revealed that BC provides the colonisation areas for anaerobic bacteria and serves as the adsorbent for substances, such as ammonia and limonene, which may hinder co-digestion (Wambugu et al., 2019). The alkaline nature of BC improves methane concentration via a reaction of carbon dioxide and H_2S with alkaline materials available in ash, consequently enhancing the biogas quality (Wang et al., 2017). Various elements and properties of BC, which influence the improvement of the CH_4 production rate, are demonstrated in Table 3. The importance of these properties for AcoD has already been discussed in Section 3.2. Additionally, BC is a thermal insulator that primarily benefits mesophilic environments, where steady temperatures are necessary for efficient methanogenesis. In this study, the highest CH_4 yield was achieved at CMR 60:40 for all groups of BMP experiments. The SMY obtained for CMR of 60:40 at HRT of 45 days were 158.98, 227.24 and 261.75 $mLg^{-1}VS^{-1}$ for groups I, II and III, respectively. At CMR of 60:40, the C/N ratio and MC were 21.9 ± 1.02 and 92.14 ± 0.07 %, respectively, indicating the optimal values for achieving the highest CH_4 yield in the AcoD of CD and VW. These values were found to align with the optimum range reported in various studies. The current investigation demonstrated that the CMR of 60:40 can be recommended as the most likely CMR for the co-digestion of CD and untreated VW.

In addition, it is desirable to incorporate a suitable dose of BC into the digester to achieve a higher methane yield. In this regard, another group of BMP experiments (set IV) was conducted at ambient conditions by adding varying quantities of water hyacinth BC, such as 5, 10, 15, 20, and 25 gL^{-1}. These digesters were designated as BCD 05, BCD 10, BCD 15, BCD 20, and BCD 25, respectively. The daily and cumulative CH_4 yield for set IV are presented in Fig. 3. The SMY for digesters BCD 05, BCD 10, BCD 15, BCD 20, and BCD 25 were found to be 199.28, 213.40, 240.07, 225.51, and 208.62 $mLCH_4/gVS$ for HRT of 45 days. Moreover, BCD 15 exhibited 16.99 %, 11.11 %, 6.06 %, and 13.10 % higher CMY than BCD 05, BCD 10, BCD 20, and BCD 25, respectively. This study reveals that blending 15 gL^{-1} water hyacinth-based BC in the CMR of 60:40 can be realised as the most significant CMR for the AcoD of CD and VW. Optimisation of CMR for AcoD provides numerous advantages, including boosting the methane yield rate, enhancing process stability, mitigating inhibition, utilising various substrates, nutrient recycling, improving system performance, and supporting environmental sustainability.

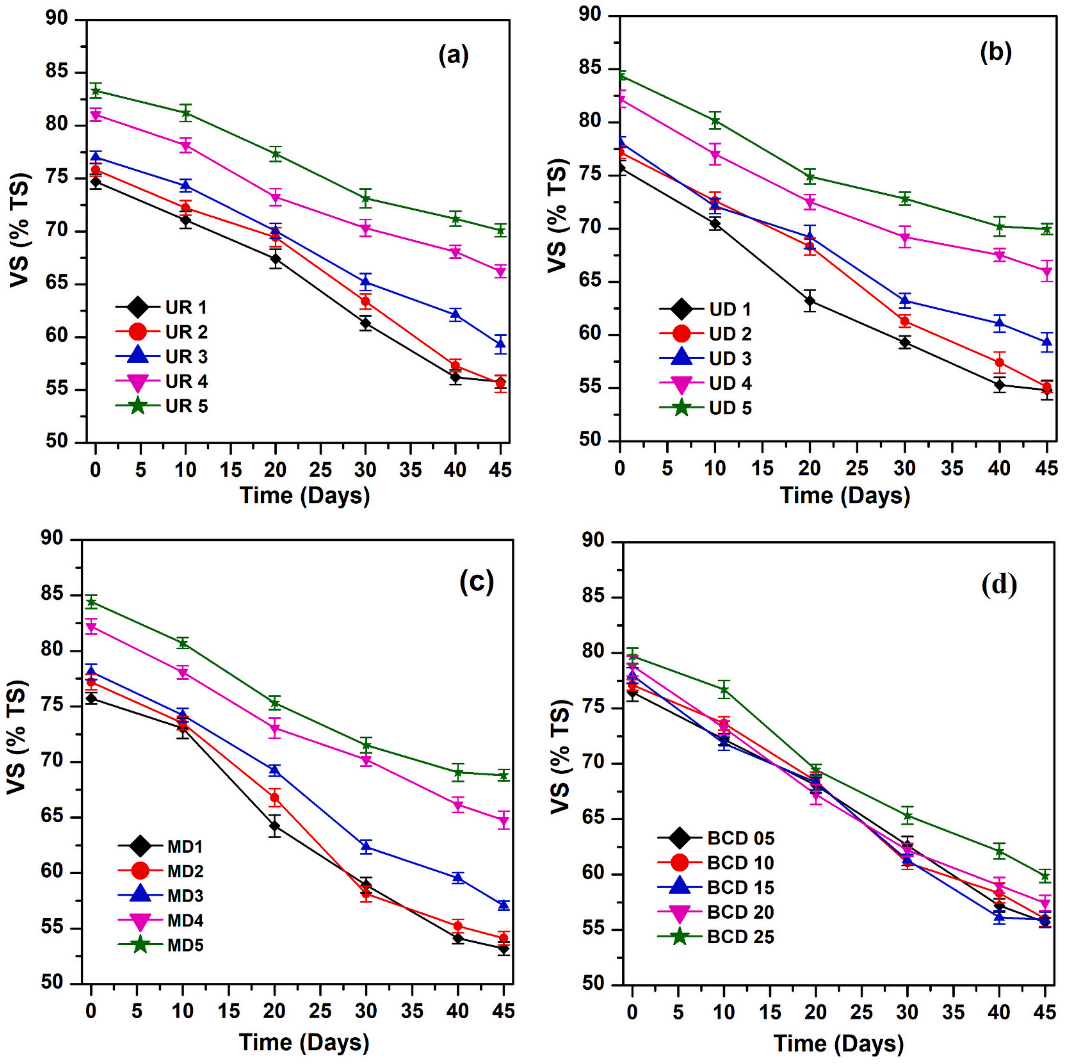


Fig. 5. Reduction of VS (% TS) concentration under (a) ambient temperature without BC, (b) ambient temperature with BC, (c) mesophilic temperatures with BC, and (d) ambient temperature with different quantities of BC for CMR 60:40.

Table 6
Modified Gompertz model parameters for AcoD of CD and VW.

CMR	Y_P (mL/gVS)			Y_R (mL/gVS-day)			λ (day)			Y_C (mL/gVS)			R^2
	Digester without BC	BC added digesters		Digester without BC	BC added digesters		Digester without BC	BC added digesters		Digester without BC	BC added digesters		
	Set I	Set II	Set III	Set I	Set II	Set III	Set I	Set II	Set III	Set I	Set II	Set III	
70:30	154.67	226.28	250.00	4.39	6.03	6.93	6.47	6.14	6.86	141.31	192.33	222.26	0.99
60:40	174.82	240.47	275.23	4.89	7.17	8.23	6.11	5.36	6.77	158.98	227.24	261.75	0.99
50:50	150.42	206.77	224.99	4.11	5.58	6.79	5.05	5.59	5.93	139.39	180.12	209.52	0.99
40:60	144.84	188.84	220.28	4.02	5.41	6.54	4.57	5.36	5.72	133.65	169.07	199.20	0.99
30:70	145.91	177.15	209.66	4.11	5.16	6.27	4.29	4.49	4.89	132.88	163.86	193.90	0.99

Set I and Set II are at ambient temperature, Set III is at mesophilic temperature, and CMR and BC stand for co-substrate mixing ratio and biochar, respectively.

3.4. *pH value and temperature*

Fig. 4 depicts the pH value recorded at ten-day intervals for all the groups of the BMP test. The decrease in pH value was observed during the first week; however, it was detected to be increased in the second week afterwards. This phenomenon occurs because acidogenic and acetogenic bacteria produce acids and CO_2 during the initial phase of co-digestion. Afterwards, the pH value rises due to the consumption of acids by methane-generating bacteria (Kwietniewska and Tys, 2014). The pH range for set I was obtained to be 4.6 to 6.5, while the incorporation of WHBC into sets II and III increased the pH levels to a range of 5.4 to 6.8. In set IV, the pH value was observed to rise as the quantity of WHBC increased. Adding 25 g/L WHBC resulted in a higher pH value of 6.3–6.9, whereas 5 g/L WHBC addition led to a lower pH range of 5.8–6.4. Several AAE metals, which were detected in the EDX analysis of the BC, improve the alkalinity level of the reactors (Aramrueang et al., 2022). Additionally, it is necessary to optimise the quantity of BC required to maintain the suitable pH range for different substrates.

Table 7
Modified Gompertz model parameters for CMR 60:40 with varying quantities of BC addition.

Digesters	Y_P (mL/gVS)	Y_R (mL/gVS-day)	λ (day)	Y_C (mL/gVS)	R^2
BCD 05	239.52	6.45	6.97	199.28	0.99
BCD 10	245.05	6.81	6.72	213.40	0.99
BCD 15	268.95	5.58	6.65	240.07	0.99
BCD 20	239.26	6.22	6.75	225.51	0.99
BCD 25	229.22	6.13	6.85	208.62	0.99

Temperature is the most crucial parameter for the evolution of microbes (Basumatary et al., 2021). In the present study, the temperature variations were recorded in intervals of 4 h for the uncontrolled digesters. However, the temperature of controlled digesters was not monitored since they were consistently maintained at a mesophilic temperature (37 ± 2 °C). The daily temperature variations recorded every 4 h for uncontrolled digesters ranged from 19.7 to 26.4 °C throughout the experimental period. The uncontrolled digesters' average temperature was below the mesophilic temperature range, resulting in a lower methane generation rate in these digesters. Thus, this study demonstrates that CH_4 production can be improved by maintaining the reactor's temperature in the mesophilic condition.

3.5. VS (% TS) degradation

Reduction in VS value helps to estimate the performance of the AD process. Fig. 5 illustrates the volatile solid reduction (VSR) analysis conducted at ten-day intervals for all BMP test sets. The VSR was evaluated using the Van Kleeck equation (Switzenbaum et al., 2003). The VSR in sets I, II and III were obtained to be 53.00–60.10 %, 57.00–63.70 %, and 59.30–65.15 %, respectively. The CMR 60:40 resulted in the highest VSR for all groups of experiments. Further, the mesophilic digesters were found to have a higher VSR value. The VSR value for CMR 60:40 of sets III was 65.14 %, higher than CMR 60:40 of sets I (60.10 %) and II (63.71 %). Similarly, the volatile solid reduction of the reactors BCD 05, BCD 10, BCD 15, BCD 20, and BCD 25 in set IV on the HRT of 45 days were calculated as 61.26, 62.20, 64.16, 63.77 and 62.05 %, respectively, exceeding the VSR for CMR 60:40 of set I. A decrease in VS favours the AcoD process, indicating increased biogas yield (Barua and Kalamdhad, 2017). The CMR with the highest VSR exhibited a higher CH_4 generation rate and vice versa.

3.6. Modified Gompertz model equation

Results of the MGM study are incorporated in Tables 6 and 7. The CMR of 60:40 resulted in a higher specific CH_4 production potential than other CMRs within their corresponding experimental groups, whereas the CMR of 30:70 exhibited a lower BMP value. Higher Y_P and Y_R values were obtained for the biochar-added mesophilic digester with a CMR of 60:40 compared to respective digesters with and without incorporation of BC performed at ambient temperature. Similarly, in the case of set IV, which was conducted by adding varying quantities of BC, 15 g/L biochar-added digester resulted in a higher CH_4 generation potential. The specific CMY potential for the digester with 15 g/L BC-added was 268.95 mL/gVS, whereas the 15 g/L BC-added digester exhibited a lesser potential (229.22 mL/gVS). Furthermore, BC 15 showed a higher value of Y_R (7.58 mL/gVS-day) compared to other reactors of set IV. This study confirms that biochar can enhance methane generation rate in the co-digestion of cattle dung and untreated vegetable waste, where 15 gL^{-1} BC bled may be considered the optimum amount of biochar required to be mixed. The curve-fitting plot of the MGM is provided in the supplementary materials (Fig. S3). The R^2 value was above 0.98, demonstrating the predicted and experimental results fit well.

4. Conclusions

Incorporating water hyacinth biochar into the AcoD of untreated vegetable waste with cattle dung has significantly enhanced the methane generation rate. This enhancement can be attributed to the porous nature of BC, which provides a colonial space for microbes. The macronutrients, alkali and alkaline earth metals of biochar enhance the slurry's alkalinity in the AD. Further, the functional groups (O—H, C—H, C═C, and C—O) increase the electron exchange among the electron donor and acceptor microorganisms. The most favourable CMR of CD and VW was identified at 60:40, as assessed by the BMP tests. Additionally, biochar-added mesophilic digesters with a 60:40 co-substrates ratio resulted in 39.26 % and 13.19 % higher CH_4 yield than those without and with biochar at ambient temperature for the BMP test period of 45 days. The addition of 15 gL^{-1} BC to AcoD of CD and VW exposed the significant quantity of BC necessary for effective blending. This study determines that blending a suitable amount of BC into AcoD can boost CH_4 production. Further studies are needed to investigate the anaerobic co-digestion of different substrates with various co-substrate mixing ratios, using different types of biochar, to determine the ideal quantity of biochar to be added for maximising methane production.

Abbreviations

AC	ash content
AcoD	anaerobic co-digestion
AD	anaerobic digestion
ASTM	American Society for Testing and Materials
BC	biochar
BET	Brunauer–Emmet–Teller
BMP	biochemical methane potential
CD	cattle dung
CMY	cumulative methane yield
DMY	daily methane yield
EDS	energy dispersive X-ray spectroscopy
FC	fixed carbon
SEM	scanning electron microscope
FT-IR	Fourier transform infrared
FW	food waste
HRT	hydraulic retention time
MC	moisture content
MGM	modified Gompertz model
CMR	co-substrates mixing ratio
SMY	specific methane yield
SDG	sustainable development goal
TSC	total solid content
UN	United Nations
VM	volatile matter
VSC	volatile solid content
VSR	volatile solid reduction
VW	vegetable waste
WH	water hyacinth
WHBC	water hyacinth biochar
XRD	X-ray diffractometer

CRediT authorship contribution statement

Shayaram Basumatary: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Harrison Hihu Muigai:** Investigation, Formal analysis, Data curation. **Pranab Goswami:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Pankaj Kalita:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that have or could be perceived to have influenced the work reported in this article.

Acknowledgement

The authors gratefully acknowledge the Science and Engineering Research Board, India (Grant number: ECR/2016/001830) for providing financial support to accomplish this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biteb.2024.102013.

Data availability

Data will be made available on request.

References

Abbassi-Guendouz, A., Brockmann, D., Trably, E., Dumas, C., Delgenès, J.P., Steyer, J.P., Escudié, R., 2012. Total solids content drives high solid anaerobic digestion via mass transfer limitation. Bioresour. Technol. 111, 55–61. https://doi.org/10.1016/j.biortech.2012.01.174.

APHA, 2017. Standard Methods for the Examination of Water and Wastewater, 23rd Editi. ed. American Public Health Association, Washington DC.

Aramrueang, N., Zhang, R., Liu, X., 2022. Application of biochar and alkalis for recovery of sour anaerobic digesters. J. Environ. Manag. 307, 114538. https://doi.org/10.1016/j.jenvman.2022.114538.

Barua, V.B., Kalamdhad, A.S., 2017. Biochemical methane potential test of untreated and hot air oven pretreated water hyacinth: a comparative study. J. Clean. Prod. 166, 273–284. https://doi.org/10.1016/j.jclepro.2017.07.231.

Basumatary, S., Das, S., Kalita, P., Goswami, P., 2021. Effect of feedstock/water ratio on anaerobic digestion of cattle dung and vegetable waste under mesophilic and thermophilic conditions. Bioresour. Technol. Rep. 14. https://doi.org/10.1016/j.biteb.2021.100675.

Basumatary, S., Goswami, P., Kalita, P., 2024. Impact of coconut husk biochar on methane production rate in batch type anaerobic digester fed with cattle dung and cooked kitchen waste. Biomass Bioenergy 187, 107300. https://doi.org/10.1016/j.biombioe.2024.107300.

Bouallagui, H., Lahdheb, H., Ben Romdan, E., Rachdi, B., Hamdi, M., 2009. Improvement of fruit and vegetable waste anaerobic digestion performance and stability with co-substrates addition. J. Environ. Manag. 90, 1844–1849. https://doi.org/10.1016/j.jenvman.2008.12.002.

Chen, L., Fang, W., Liang, J., Nabi, M., Cai, Y., Wang, Q., Zhang, P., Zhang, G., 2023. Biochar application in anaerobic digestion: Performances, mechanisms, environmental assessment and circular economy. Resour. Conserv. Recycl. 188, 106720. https://doi.org/10.1016/j.resconrec.2022.106720.

COP28, 2023. Global Cooling Pledge for COP28. URL. https://www.cop28.com/en/global-cooling-pledge-for-cop28. (Accessed 21 May 2024).

Deepanraj, B., Sivasubramanian, V., Jayaraj, S., 2017. Effect of substrate pretreatment on biogas production through anaerobic digestion of food waste. Int. J. Hydrog. Energy 42, 26522–26528. https://doi.org/10.1016/j.ijhydene.2017.06.178.

Domingues, R.R., Trugilho, P.F., Silva, C.A., De Melo, I.C.N.A., Melo, L.C.A., Magriotis, Z. M., Sánchez-Monedero, M.A., 2017. Properties of biochar derived from wood and high-nutrient biomasses with the aim of agronomic and environmental benefits. PLoS One 12, 1–19. https://doi.org/10.1371/journal.pone.0176884.

Ighalo, J.O., Conradie, J., Ohoro, C.R., Amaku, J.F., Oyedotun, K.O., Maxakato, N.W., Akpomie, K.G., Okeke, E.S., Olisah, C., Malloum, A., Adegoke, K.A., 2023. Biochar from coconut residues: an overview of production, properties, and applications. Ind. Crop. Prod. 204, 117300. https://doi.org/10.1016/j.indcrop.2023.117300.

Indren, M., Birzer, C.H., Kidd, S.P., Medwell, P.R., 2020. Effect of total solids content on anaerobic digestion of poultry litter with biochar. J. Environ. Manag. 255, 109744. https://doi.org/10.1016/j.jenvman.2019.109744.

Jiang, Q., Chen, Y., Yu, S., Zhu, R., Zhong, C., Zou, H., Gu, L., He, Q., 2020. Effects of citrus peel biochar on anaerobic co-digestion of food waste and sewage sludge and its direct interspecies electron transfer pathway study. Chem. Eng. J. 398. https://doi.org/10.1016/j.cej.2020.125643.

Johnravindar, D., Kaur, G., Liang, J., Lou, L., Zhao, J., Manu, M.K., Kumar, R., Varjani, S., Wong, J.W.C., 2022. Impact of total solids content on biochar amended co-digestion of food waste and sludge: microbial community dynamics, methane production and digestate quality assessment. Bioresour. Technol. 361, 127682. https://doi.org/10.1016/j.biortech.2022.127682.

Kaur, G., Johnravindar, D., Wong, J.W.C., 2020. Enhanced volatile fatty acid degradation and methane production efficiency by biochar addition in food waste-sludge co-digestion: a step towards increased organic loading efficiency in co-digestion. Bioresour. Technol. 308, 123250. https://doi.org/10.1016/j.biortech.2020.123250.

Kothari, R., Pandey, A.K., Kumar, S., Tyagi, V.V., Tyagi, S.K., 2014. Different aspects of dry anaerobic digestion for bio-energy: an overview. Renew. Sust. Energ. Rev. 39, 174–195. https://doi.org/10.1016/j.rser.2014.07.011.

Kumar, M., Dutta, S., You, S., Luo, G., Zhang, S., Show, P.L., Sawarkar, A.D., Singh, L., Tsang, D.C.W., 2021. A critical review on biochar for enhancing biogas production from anaerobic digestion of food waste and sludge. J. Clean. Prod. 305, 127143. https://doi.org/10.1016/j.jclepro.2021.127143.

Kwietniewska, E., Tys, J., 2014. Process characteristics, inhibition factors and methane yields of anaerobic digestion process, with particular focus on microalgal biomass fermentation. Renew. Sust. Energ. Rev. 34, 491–500. https://doi.org/10.1016/j.rser.2014.03.041.

Lay, J.-J., Li, Y.-Y., Noike, T., 1997. Influences of pH and moisture content on the methane production in high-solids sludge digestion. Water Res. 31, 1518–1524. https://doi.org/10.1016/S0043-1354(96)00413-7.

Li, P., Wang, Q., He, X., Yu, R., He, C., Shen, D., Jiao, Y., 2022. Investigation on the effect of different additives on anaerobic co-digestion of corn straw and sewage sludge: comparison of biochar, Fe3O4, and magnetic biochar. Bioresour. Technol. 345, 126532. https://doi.org/10.1016/j.biortech.2021.126532.

Liu, H., Wang, X., Fang, Y., Lai, W., Xu, S., Lichtfouse, E., 2022. Enhancing thermophilic anaerobic co-digestion of sewage sludge and food waste with biogas residue biochar. Renew. Energy 188, 465–475. https://doi.org/10.1016/j.renene.2022.02.044.

Liu, M., Li, Z., Qi, X.e., Chen, Z., Ni, H., Gao, Y., Liu, X., 2023. Improvement of cow manure anaerobic digestion performance by three different crop straw biochars. Environ. Technol. Innov. 31, 103233. https://doi.org/10.1016/j.eti.2023.103233.

Mao, C., Feng, Y., Wang, X., Ren, G., 2015. Review on research achievements of biogas from anaerobic digestion. Renew. Sust. Energ. Rev. 45, 540–555. https://doi.org/10.1016/j.rser.2015.02.032.

NIU, 2023. Typical IR Absorption Frequencies for Common Functional Groups [WWW Document]. North. Illinois Univ. Dep. Chem. Biochem.. URL. https://www.niu.edu/clas/chembio/research/analytical-lab/ftir/ir-frequencies-table.shtml. (Accessed 23 May 2023)

Odejobi, O.J., Ajala, O.O., Osuolale, F.N., 2021. Anaerobic co-digestion of kitchen waste and animal manure: a review of operating parameters, inhibiting factors, and pretreatment with their impact on process performance. Biomass Convers. Biorefinery 5515–5531. https://doi.org/10.1007/s13399-021-01626-3.

Osei-Owusu, B.A., Baidoo, M.F., Arthur, R., Oduro-Kwarteng, S., 2023. Physico-chemical characterization of selected feedstocks as co-substrates for household biogas generation in Ghana. Int. J. Sustain. Eng. 16, 117–128. https://doi.org/10.1080/19397038.2023.2214167.

Ovi, D., Chang, S.W., Wong, J.W.C., Johnravindar, D., Varjani, S., Hoon Jeung, J., Chung, W.J., Thirupathi, A., Ravindran, B., 2022. Effect of rice husk and palm tree-based biochar addition on the anaerobic digestion of food waste/sludge. Fuel 315, 123188. https://doi.org/10.1016/j.fuel.2022.123188.

Pan, J., Ma, J., Liu, X., Zhai, L., Ouyang, X., Liu, H., 2019. Effects of different types of biochar on the anaerobic digestion of chicken manure. Bioresour. Technol. 275, 258–265. https://doi.org/10.1016/j.biortech.2018.12.068.

Ren, Y., Yu, M., Wu, C., Wang, Q., Gao, M., Huang, Q., 2018. A comprehensive review on food waste anaerobic digestion : research updates and tendencies. Bioresour. Technol. 247, 1069–1076. https://doi.org/10.1016/j.biortech.2017.09.109.

Sahota, S., Vijay, V.K., Subbarao, P.M.V., Chandra, R., Ghosh, P., Shah, G., Kapoor, R., Vijay, V., Koutu, V., Thakur, I.S., 2018. Characterization of leaf waste based biochar for cost effective hydrogen sulphide removal from biogas. Bioresour. Technol. 250, 635–641. https://doi.org/10.1016/j.biortech.2017.11.093.

Sejian, V., Raghavendra, B., Kumar, M.P., Bagath, M., Saif, A.-H.Y.A., Sullivan, M., B., G. J., 2016. Livestock as sources of greenhouse gases and its significance to climate change. In: Bernardo, Llamas, Juan, P. (Eds.), Greenhouse Gases. Intech Open, London, UK, pp. 244–259. https://doi.org/10.5772/62135.

Shen, B., Li, G., Wang, F., Wang, Y., He, C., Zhang, M., Singh, S., 2015. Elemental mercury removal by the modified bio-char from medicinal residues. Chem. Eng. J. 272, 28–37. https://doi.org/10.1016/j.cej.2015.03.006.

Shen, R., Jing, Y., Feng, J., Luo, J., Yu, J., Zhao, L., 2020. Performance of enhanced anaerobic digestion with different pyrolysis biochars and microbial communities. Bioresour. Technol. 296, 122354. https://doi.org/10.1016/j.biortech.2019.122354.

Sun, C., Liu, F., Song, Z., Wang, J., Li, Y., Pan, Y., Sheng, T., Li, L., 2019. Feasibility of dry anaerobic digestion of beer lees for methane production and biochar enhanced performance at mesophilic and thermophilic temperature. Bioresour. Technol. 276, 65–73. https://doi.org/10.1016/j.biortech.2018.12.105.

Sun, Z., Feng, L., Li, Y., Han, Y., Zhou, H., Pan, J., 2022. The role of electrochemical properties of biochar to promote methane production in anaerobic digestion. J. Clean. Prod. 362, 132296. https://doi.org/10.1016/j.jclepro.2022.132296.

Suthar, S., Sharma, B., Kumar, K., Rajesh Banu, J., Tyagi, V.K., 2022. Enhanced biogas production in dilute acid-thermal pretreatment and cattle dung biochar mediated biomethanation of water hyacinth. Fuel 307, 121897. https://doi.org/10.1016/j.fuel.2021.121897.

Switzenbaum, M.S., Farrell, J.B., Pincince, A.B., 2003. Relationship between the Van Kleeck and mass-balance calculation of volatile solids loss. Water Environ. Res. 75, 377–380. https://doi.org/10.2175/106143003x141187.

Syaichurrozi, I., 2018. Biogas production from co-digestion Salvinia molesta and rice straw and kinetics. Renew. Energy 115, 76–86. https://doi.org/10.1016/j.renene.2017.08.023.

Tian, Y., Yang, K., Zheng, L., Han, X., Xu, Y., Li, Y., Li, S., Xu, X., Zhang, H., Zhao, L., 2020. Modelling biogas production kinetics of various heavy metals exposed anaerobic fermentation process using sigmoidal growth functions. Waste Biomass Valoriz. 11, 4837–4848. https://doi.org/10.1007/s12649-019-00810-x.

U.S. EPA (U.S. Environmental Protection Agency), 2021. From Farm to Kitchen: The Environmental Impacts of US Food Waste. U.S. Environ. Prot. Agency. URL. https://www.epa.gov/system/files/documents/2021-11/from-farm-to-kitchen-the-environmental-impacts-of-u.s.-food-waste_508-tagged.pdf. (Accessed 14 March 2023).

Wambugu, C.W., Rene, E.R., van de Vossenberg, J., Dupont, C., van Hullebusch, E.D., 2019. Role of biochar in anaerobic digestion based biorefinery for food waste. Front. Energy Res. 7, 1–13. https://doi.org/10.3389/fenrg.2019.00014.

Wang, D., Ai, J., Shen, F., Yang, G., Zhang, Y., Deng, S., Zhang, J., Zeng, Y., Song, C., 2017. Improving anaerobic digestion of easy-acidification substrates by promoting buffering capacity using biochar derived from vermicompost. Bioresour. Technol. 227, 286–296. https://doi.org/10.1016/j.biortech.2016.12.060.

Wang, K., Yun, S., Ke, T., An, J., Abbas, Y., Liu, X., Zou, M., Liu, L., Liu, J., 2022. Use of bag-filter gas dust in anaerobic digestion of cattle manure for boosting the methane yield and digestate utilization. Bioresour. Technol. 348, 126729. https://doi.org/10.1016/j.biortech.2022.126729.

Wang, Y., Mu, L., Chen, C., Xu, F., Peng, H., Song, Y., Chen, G., 2024. Preparation of iron oxide-modified digestate biochar and effect on anaerobic digestion of kitchen waste. Bioresour. Technol. 398, 130515. https://doi.org/10.1016/j.biortech.2024.130515.

Xie, Y., Wang, L., Li, H., Westholm, L.J., Carvalho, L., Thorin, E., Yu, Z., Yu, X., Skreiberg, Ø., 2022. A critical review on production, modification and utilization of biochar. J. Anal. Appl. Pyrolysis 161. https://doi.org/10.1016/j.jaap.2021.105405.

Zhang, M., Wang, Y., 2021. Impact of biochar supported nano zero-valent iron on anaerobic co-digestion of sewage sludge and food waste: methane production, performance stability and microbial community structure. Bioresour. Technol. 340, 125715. https://doi.org/10.1016/j.biortech.2021.125715.

Zhao, W., Yang, H., He, S., Zhao, Q., Wei, L., 2021. A review of biochar in anaerobic digestion to improve biogas production: performances, mechanisms and economic assessments. Bioresour. Technol. 341, 125797. https://doi.org/10.1016/j.biortech.2021.125797.