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Enhanced Biogas Production from the Anaerobic Batch Treatment of Banana Peels

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ABSTRACT

Waste disposal management and the energy crisis are important challenges facing most countries. The fruit-processing industry generates daily several tons of wastes, of which the major share comes from banana farms. Anaerobic digestion (AD) technology has been applied to the treatment of wastewater, animal slurry, food waste, and agricultural residues, with the primary goals of energy production and waste elimination. This study examines the effect of organic loading (OL) and cow manure (CM) addition on AD performance when treating banana peel waste (BPW). The maximum daily biogas production rates of banana peels (BPs) with a CM content of 10%, 20%, and 30% at 18 and 22 g of volatile solids (g_{vs}) per liter were 50.20, 48.66, and 62.78 $mL·(g_{vs}·d)^{-1}$ and 40.49, 29.57, and 46.54 $mL·(g_{vs}·d)^{-1}$, respectively. However, the daily biogas yield showed no clear interdependence with OL or CM content. In addition, a kinetic analysis using first-order and cone models showed that the kinetic parameters can be influenced by the process parameters.

1. Introduction

Bananas are the second largest fruit crop cultivated in the past decade, with an approximate gross global production of approximately 1.2×10^8 t. India, China, Philippines, and Ecuador are the largest global producers of bananas, and the banana-processing industry is a critical branch of domestic development [1]. An immediate solution for the production of cheap sustainable energy from banana waste is required [2]. Several tons of peels, fibers, and leaves are generated during the production and processing of bananas [3,4]. Therefore, sustainable agricultural practices must be applied in order to avoid environmental problems [5–7]. Energy conservation and waste management are among the challenges facing most nations [8,9]. The application of waste-to-energy technologies would solve the problem of waste accumulation, which is coupled with the elimination of emissions from waste [10–14].

Fruit waste is an organic waste commodity that can be anaerobically treated for sustainable energy production [15,16]. Anaerobic digestion (AD) of waste has been broadly acknowledged as a sustainable treatment technique that generates a high-value gaseous product. During the decomposition of waste under anaerobic conditions, organic matter is converted to biogas through microbial activities [17]. Biogas (approximate 60% CH_4 and 40% CO_2) is considered to be a green gaseous biofuel and can be used for heating, electricity, and vehicle fuel production [18].

Three main biochemical steps embody the AD process: hydrolysis/fermentation, acidogenesis, and methanogenesis [19–23]. AD technology has been applied for the treatment of wastewater, animal slurry, food waste, and agricultural residue, with the primary goals of energy production and waste elimination [24–27]. Over the last 15 years, the combined degradation of organic waste has gained attention from several researchers. This method, which is known as co-digestion, enhances the conversion rate as a result of the synergistic effect of the different organic co-substrates [28,29].

Monitoring the process parameters during AD is crucial for the stable operation of the digesters [30]. The organic loading (OL) is an important parameter in the smooth and stable operation of a reactor, and overloading can cause the digester to turn sour [31,32]. The use of sludge with a low carbon/nitrogen (C/N) ratio is a key factor in the decomposition of fruit and vegetable wastes [33,34]. In comparison with mono-digestion, the co-digestion of fruit wastes with various animal slurries has a positive effect on biogas yield, as it increases the buffer capacity to maintain an optimal pH for methanogenic bacteria, provides a better C/N ratio

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within the digester, and makes use of all the various nutrients and diverse microorganisms. Several studies refer to an optimal C/N ratio range of 20–30; however, this range differs significantly from the C/N ratio range of 40–70 that is provided by agricultural waste [35,36]. The AD of fruit-processing waste has not been much studied, and information on banana peel waste (BPW) is limited. Recalcitrance due to a higher content of lignin in banana peels (BPs) is an impediment to the degradation of the substrates and may hinder process performance [37].

As only a few studies have examined the bioenergy potential of BPs [38–40], a deeper investigation is necessary in order to address the energy demand and enormous amount of organic waste in banana processing. The objectives of this batch study were: ① to examine the effect of OL on biogas potential in the AD of BPs; ② to clarify how the addition of cow manure (CM) enhances AD performance; and ③ to provide insight into the kinetics of the AD process.

2. Materials and methods

2.1. Inoculum and substrates

The inoculum used in this study was collected from a mesophilic digester that anaerobically treats wastewater at the wastewater treatment plant (WWTP) of Garmerwolde in the province of Groningen, the Netherlands. Fresh CM was collected from a local farmer in Groningen. Prior to their characterization and use, both sludge and manure were stored at 6 °C to avoid undesirable fermentation processes. Fresh bananas were obtained from a local market. The fresh ripened BPs were cut into pieces of approximately 0.5 cm × 0.5 cm in size, and then washed thoroughly with deionized water to remove physically adsorbed contamination. The BPs were homogenized for 30 s with a homogenizer mixer (RW-20 S1; Janke & Kunkel, Germany) before use.

2.2. Experimental design

An anaerobic batch system (R1 → R16) was established in order to examine the influence of the OL and the addition of CM on biogas yield during BP digestion. All batch digestion experiments were carried out in 300 mL glass serum bottles with a working volume of 240 mL. Different CM contents were required to determine the degradation characteristics of BPs at different concentrations. The different OLs were set at 10, 14, 18, and 22 g of volatile solids (VSs; g_{vs}) per liter, and the proportion of CM was set to 10%, 20%, and 30%. The inoculum-to-substrate ratio (ISR) was maintained at 2, according to the literature [15,31]. Assays with inoculum alone were used as control samples. The content of the test systems is given in Table 1. The initial VS concentrations of the inoculum and substrate were calculated based on the predetermined ISR. For all experiments, an appropriate volume of distilled water was added to reach a final volume of 240 mL. The initial pH was then adjusted to 7.0 ± 0.2 using 1 mol·L^{-1} HCl. All reactors were sealed and flushed with pure nitrogen for 3 min to ensure anaerobic conditions. Thereafter, they were placed in an incubator, maintained at a constant mesophilic temperature (36 ± 1) °C, and shaken manually twice per day during the experimental period of the assay. Blank trials containing sludge were only carried out to correct the biogas levels produced by the inoculum. After biogas production stopped, the residuals were sampled to determine VS removal. Triplicate bottles were used in all experiments, and all values are means of triplicates ± standard deviation.

2.3. Analytical methods and calculation

The concentrations of total solid (TS; g·kg^{-1}) and total VS (g·kg^{-1}) were set according to the recommendations of the *Standard Methods for the Examination of Water and Wastewater* of the American Public Health Association (APHA) [42]. The pH was determined offline using a pH meter (HI-991001; Hanna Instruments, USA). Chemical oxygen demand (COD; g·kg^{-1}) was determined using a test kit (Hach Lange GmbH, Germany) according to the manufacturer's instructions, and was quantified by a spectrophotometer (DR/2010; Hach Company, USA).

The quantity of lignocelluloses in BPs and CM was determined according to the procedures established by the National Renewable Energy Laboratory (NREL) [43]. The concentrations of monosaccharides were determined by high-performance liquid chromatography (LC 1200 Series; Agilent Technologies, Inc., USA). The monosaccharides (glucose, xylose, arabinose, mannose, and galactose) were analyzed on a Bio-Rad Aminex HPX-87H column (300 mm × 7.8 mm) operated at 60 °C with 0.0005 mol·L^{-1} H_2SO_4 as an eluent at a flow rate of 0.05 mL·min^{-1}. The content of the acid-soluble lignin was estimated gravimetrically and was determined using an ultraviolet detector at 205 nm with an extinction coefficient of 110 L·(g·cm)$^{-1}$.

The biogas composition was determined using a micro gas chromatograph single-channel two-stream selector system (Thermo Fisher Scientific Inc., USA) equipped with a chromatographic

Table 1
Experimental conditions of the batch tests.

Reactor	Experimental design			
	ISR[a]	CM content (%)[a]	OL (g_{vs}·L^{-1})	Replicates
R1	2	0	10	3
R2	2	10	10	3
R3	2	20	10	3
R4	2	30	10	3
R5	2	0	14	3
R6	2	10	14	3
R7	2	20	14	3
R8	2	30	14	3
R9	2	0	18	3
R10	2	10	18	3
R11	2	20	18	3
R12	2	30	18	3
R13	2	0	22	3
R14	2	10	22	3
R15	2	20	22	3
R16	2	30	22	3

[a] Based on volatile solids.

column (HP-PLOT U; Agilent Technologies, Inc., USA) with helium as the carrier gas at a total flow of 10 mL. A gas with standard composition (50% (v/v) CH_4, 20% (v/v) CO_2, and 30% (v/v) N_2) was used to calibrate and adjust the chromatographic results. The calibration curves of the above gas components were linear and reproducible.

The daily amount of biogas produced (mL·$(g_{vs}·d)^{-1}$) was determined using a water displacement method. The gas equipment used in this work was capable of providing biogas data within 5% accuracy [44]. Technical digestion time—the time needed to produce 80% of the maximal biogas amount—is another indicator of biogas production performance [45]. In this study, evaluation of biogas production was based on corrected biogas and methane yields according to standard temperature and pressure. The daily biogas volume was normalized (T = 0 °C, P = 1 bar (1 bar = 10^5 Pa)) according to Eq. (1) [46]:

$$V_N = \frac{V \times 273 \times (760 - p_w)}{(273 + T) \times 760} \tag{1}$$

where V_N is the volume of the dry biogas under standard conditions (mL), V is the volume of the biogas (mL), p_w is the water vapor pressure as a function of ambient temperature (mmHg, 1 mmHg ≈ 133.322 Pa), and T is the ambient temperature (°C).

2.4. Kinetic study

Biogas production was modeled by fitting the experimental data with two kinetic models. Regression analysis was conducted in Microsoft Office Excel (Microsoft Office 2010) and MATLAB 2016b. The first-order model and cone model were used for the hydrolysis of organic matter and are described by Eqs. (2) and (3) [47–49]:

$$B(t) = B_o \times \left[1 - e^{(-Kt)}\right] \tag{2}$$

$$B(t) = \frac{B_o}{1 + (Kt)^{-n}} \tag{3}$$

where $B(t)$ is the cumulative biogas yield at t days (mL·g_{vs}^{-1}), B_o is the maximum biogas potential of the substrate (mL·g_{vs}^{-1}), n is the shape factor, K is the biogas production rate constant (i.e., the first-order disintegration rate constant) (d^{-1}), and t is the time (d).

The predicted biogas yields obtained from the two models were plotted with the experimental biogas yield. The correlation coefficient (R^2) was calculated in order to validate the models.

3. Results and discussion

3.1. Characterization of inoculum and substrates

Table 2 summarizes the characteristics of the anaerobic inoculum, BPW, and CM. It is notable that the characteristics of the inoculum and CM were different for the two experimental periods. The VS/TS ratio of the BPW was 0.87, while that of the CM was 0.78–0.86, indicating that the BPW contained slightly more digestible organic matter than the CM. The VS/TS ratio and COD values of the CM in this study were similar to those reported by Fantozzi and Buratti [50]. The mixture of BPW and CM was expected to improve the efficiency of the AD, in comparison with using BPW alone. Other studies analyzing the structural carbohydrates, lignin, and ash content of materials such as office paper or cardboard have reported similar concentration ranges [41].

Table 2
Physical and chemical characteristics of the anaerobic inoculum, BPW, and CM used in the batch tests.

Parameter	Inoculum	BPW	CM
TS (g·kg^{-1})	47.56 ± 0.10	79.25 ± 2.27	190.03 ± 10.41
VS (g·kg^{-1})	30.09 ± 0.22	69.03 ± 2.09	164.00 ± 3.88
VS/TS	0.63	0.87	0.86
COD (g·kg^{-1})	47.27 ± 0.73	152.68 ± 10.17	184.37 ± 13.30
pH	7.36	—	—
Cellulose (% TS)	ND	52.43 ± 2.81	17.21 ± 1.34
Hemicellulose (% TS)	ND	37.19 ± 1.64	16.42 ± 0.80
Insoluble lignin (% TS)	0.95 ± 0.18	5.85 ± 0.78	27.19 ± 2.02
Soluble lignin (% TS)	0.76 ± 0.04	1.89 ± 0.15	1.64 ± 0.63
Extractives	ND	7.26 ± 1.58	29.03 ± 3.19
Ash (% TS)	1.26 ± 0.38	1.03 ± 0.17	4.38 ± 1.02

Values are the averages of three determinations. ND: not determined.

3.2. Daily biogas yield depending on OL and CM content

Fig. 1 gives the daily biogas production (mL·$(g_{vs}·d)^{-1}$) with different CM content for four OLs. Biogas production began rapidly on the first day of digestion in all of the digesters. The maximum daily biogas production rate of BPs with CM contents of 10%, 20%, and 30% at 10 g_{vs}·L^{-1} were 112.18, 89.56, and 94.01 mL·$(g_{vs}·d)^{-1}$, respectively. A similar trend was shown by the reactors with CM contents of 10%, 20%, and 30% at 14 g_{vs}·L^{-1}, which reached maximum daily biogas yields of 100.17, 96.93, and 79.96 mL·$(g_{vs}·d)^{-1}$, respectively. The daily biogas production at 10 and 14 g_{vs}·L^{-1} fluctuated between Day 2 to Day 8 of digestion with a range of 40–80 mL·$(g_{vs}·d)^{-1}$, and then dropped to a lower level.

Biogas production rates were observed to be lower for higher OLs and continued at a lower level during the experiment. The maximum daily biogas production rates of BPs with CM contents of 10%, 20%, and 30% at 18 and 22 g_{vs}·L^{-1} were 50.20, 48.66, and 62.78 mL·$(g_{vs}·d)^{-1}$ and 40.49, 29.57, and 46.54 mL·$(g_{vs}·d)^{-1}$, respectively. The daily biogas yield showed no clear interdependence with the OL or CM content.

3.3. Cumulative biogas yield depending on OL and CM content

As described above, in an effort to improve the performance of the AD of BPs, CM was added in proportions of 10%, 20%, and 30%. As shown in Fig. 2 and Table 3, the biogas yields of BP at 10 g_{vs}·L^{-1} with CM content of 10%, 20%, and 30% were 514.87, 496.95, and 426.43 mL·g_{vs}^{-1}, respectively. The biogas yield increased by 12.5% at the CM content of 10% with regard to experimental set R1, which had no CM, thus confirming that CM has a positive effect on AD performance.

Conversely, as the CM content increased to 30%, the biogas yield decreased by 17.2% compared with a CM content of 10%. One possible reason for the lower biogas yield could be the barely degradable lignocellulosic material contained in the manure. A high lignin content results in lower biogas yields, as reported by Chiumenti et al. [51]. Biogas yields from BP at 14 and 18 g_{vs}·L^{-1} showed different patterns.

Similar studies on the digestion of BPs showed lower cumulative methane yield than was found in the current study; this difference might be related to the inoculum and its activity, which affects the degradation of hemicellulose components from the enzymes [52–55]. Nathoa et al. [56] reported elevated methane production in two-phase fermentation, with the separation of the hydrolysis/acidification and methanogenesis steps resulting in higher conversion efficiencies.

CM enhanced the AD performance as was expected, as it contains active microorganisms for biogas production. During the co-digestion of BPs with CM and the operation of the digesters at different OLs, the ISR was maintained at 2, as this ratio has been previously shown to have significant buffering capacity, and to thus maintain an optimal pH for methanogenic bacteria [31,57]. The anaerobic mono-digestion of BPs (experimental sets R1, R5,

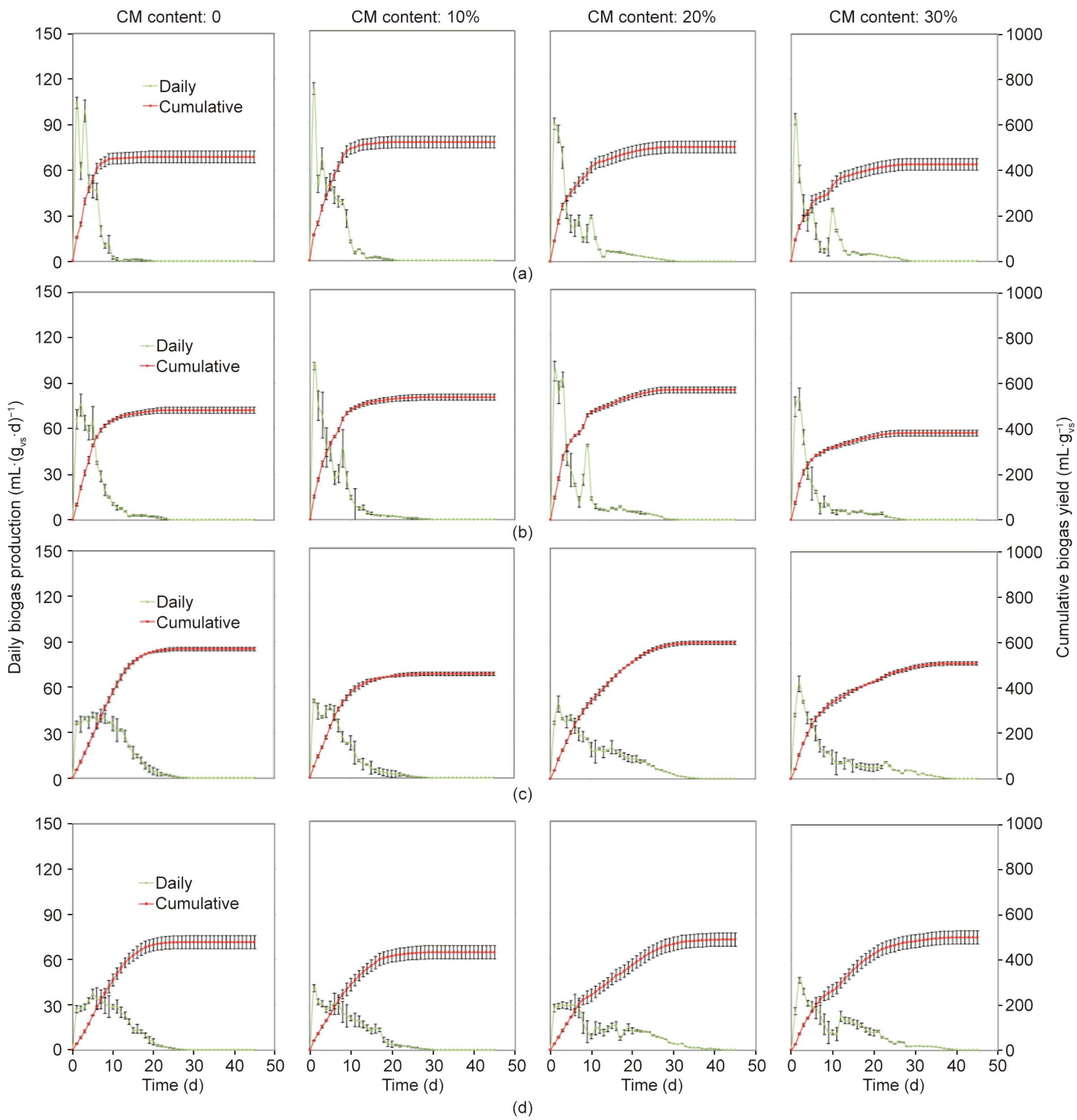

Fig. 1. Daily biogas production rate and cumulative biogas yield of BPs with four different CM contents and four different OLs: (a) 10 $g_{vs}{\cdot}L^{-1}$, (b) 14 $g_{vs}{\cdot}L^{-1}$, (c) 18 $g_{vs}{\cdot}L^{-1}$, and (d) 22 $g_{vs}{\cdot}L^{-1}$.

R9, and R13) did not show clear results. As in the anaerobic mono-digestion of BPs, biogas production was observed after Day 6 in the co-digestion experiments. It is notable that the mono-digestion sets (R1, R5, R9, and R13) showed a high methane content at the four OLs of 10, 14, 18, and 22 $g_{vs}{\cdot}L^{-1}$, reaching 63.4%, 64.6%, 62.0%, and 62.6%, respectively (Table 3). The corresponding biogas yields at these OLs were calculated to be 457.79, 481.67, 568.37, and 476.51 $mL{\cdot}g_{vs}^{-1}$, respectively. Controversially, a lower methane content and yield were found for the co-digestion of BPs with 30% CM for all OLs. The methane content for R8, R12, and R16 was 53.1%, 54.7%, and 53.4%, respectively.

The results (Fig. 2) also indicated that the cumulative biogas yield did not increase linearly with respect to an increase in the CM content at 10 and 14 $g_{vs}{\cdot}L^{-1}$, but rather followed a curve. The functional relationships between cumulative biogas yield and CM content at 10 and 14 $g_{vs}{\cdot}L^{-1}$ were found to be $y = -0.32x^2 + 8.54x + 459.11$ ($R^2 = 0.9927$) and $y = -0.5818x^2 + 14.801x + 471.75$ ($R^2 = 0.8966$), respectively. At 18 and 22 $g_{vs}{\cdot}L^{-1}$, the results showed a linear correlation of cumulative biogas yield and CM content with $y = -0.4306x + 536.38$ ($R^2 = 0.0081$) and $y = 1.2714x + 452.66$ ($R^2 = 0.2748$), respectively.

From another aspect, the full-scale biogas production presented load fluctuation during operation. Therefore, the functional relationship between biogas yield and OL was examined. As shown in Fig. 3, all the sets showed nonlinear correlation; the functional relationships at CM contents of 0, 10%, 20%, and 30% were $y = -1.8085x^2 + 61.443x + 12.132$ ($R^2 = 0.6$), $y = -0.6665x^2 + 12.788x + 461.09$ ($R^2 = 0.8501$), $y = -2.7365x^2 + 87.13x - 105.19$ ($R^2 = 0.9502$), and $y = 0.566x^2 - 9.4095x + 448.72$ ($R^2 = 0.5797$), respectively, indicating an unclear relationship when staggering the CM content in the reactor sets. Similarly, the positive effect of CM in this paper was consistent with previously reported results [58,59].

As shown in Table 3, the technical digestion time did not follow the tendency of the biogas performance. Pellera and Gidarakos [57] verified that lower technical digestion times were observed in the

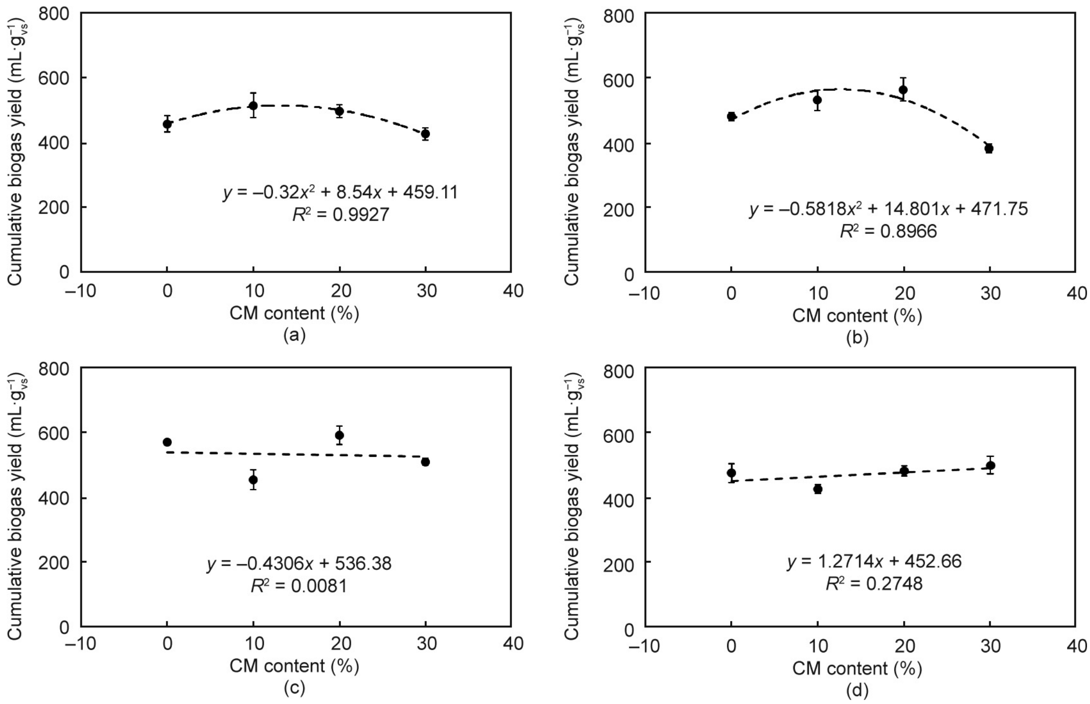

Fig. 2. Effect of CM content on the cumulative biogas yield from BPs at different initial OLs: (a) 10 $g_{vs}·L^{-1}$, (b) 14 $g_{vs}·L^{-1}$, (c) 18 $g_{vs}·L^{-1}$, and (d) 22 $g_{vs}·L^{-1}$.

Table 3
Biogas yield, methane content, and VS removal rate of BPs with different CM contents under four OLs.

Reactor	Biogas yield (mL·g_{vs}^{-1})	Methane content (%)	Methane yield (mL·g_{vs}^{-1})	VS removal rate (%)	T_{80} (d)
R1	457.79 ± 25.59	63.4	290.24	28.02 ± 3.37	6
R2	514.87 ± 38.30	59.3	305.32	29.68 ± 3.57	8
R3	496.95 ± 20.99	57.2	284.26	28.07 ± 1.29	10
R4	426.43 ± 18.67	59.5	253.73	23.65 ± 5.02	11
R5	481.67 ± 12.78	64.6	311.16	28.18 ± 0.25	7
R6	531.83 ± 31.31	59.7	317.50	32.07 ± 1.40	8
R7	654.81 ± 35.85	60.8	343.40	33.11 ± 1.37	18
R8	382.27 ± 13.90	53.1	202.99	18.86 ± 0.95	9
R9	568.37 ± 7.72	62.0	352.39	32.47 ± 2.94	13
R10	452.99 ± 31.20	58.2	263.64	24.80 ± 1.73	10
R11	589.99 ± 28.78	59.4	350.45	38.62 ± 4.09	18
R12	508.35 ± 10.40	54.7	278.07	30.25 ± 3.81	17
R13	476.51 ± 29.00	62.6	298.30	26.11 ± 0.97	13
R14	427.29 ± 13.70	58.9	251.67	22.93 ± 1.45	14
R15	482.72 ± 15.29	54.1	261.15	27.34 ± 2.18	22
R16	500.42 ± 26.44	53.4	267.22	31.93 ± 4.06	18

T_{80}: the time needed for 80% biogas production.

AD of olive pomace at an ISR of 4 than at ISRs of 0.5–1. Opinions vary regarding whether or not methane yield is the best indicator of impending reactor failure; different authors have suggested strong monitoring of the total volatile fatty acid/total alkalinity (TVFA/TA) ratio and have identified ratios below 0.3 as optimal for smooth digester operation. A high bicarbonate concentration most likely contributes to the buffering of the system. Animal manures have a high alkaline capacity, making them suitable substrates for AD [60].

Combined digestion of various wastes not only provides a sufficient C/N ratio, but also dilutes toxic compounds [61]. Considering the above results, the partial addition of CM is an efficient solution for farm-scale digesters as well as a sustainable solution with ecological benefits [62]. A financial evaluation would be interesting in order to assess factors other than the co-substrate fraction and OL for full-scale applications [63,64].

3.4. VS removal depending on OL and CM content

In order to examine the degradation efficiency and correspondence with the biogas yields, VS removal rate was determined. Table 3 presents the VS removal rate for all the reactors. R11 showed the highest VS removal rate of 38.62%, followed by R7, R9, and R6 with removal rates of 33.11%, 32.47%, and 32.07%, respectively.

The mono-digestion showed rapid biogas production which was likely due to the release of oligomers and monomeric sugars, which in turn affected the reactivity of the polymers. Elevated VS degradation could be due to the sludge availability (ISR of 2) providing buffering capacity and sufficient methanogens, which could hinder the accumulation of volatile fatty acids inside the bioreactor and lead to a stable pH. It has been shown that pH values in the range 6.5–7.5 favor the growth and activity of methanogens [65].

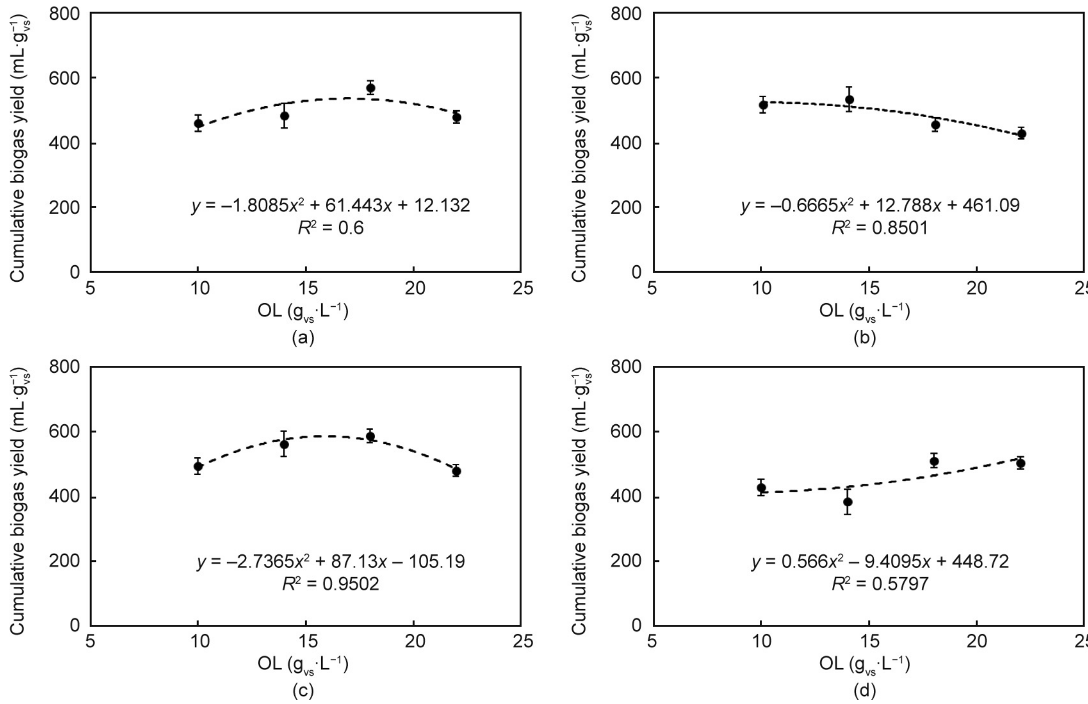

Fig. 3. Effect of initial OL on the cumulative biogas yield from BPs at different CM contents: (a) no CM, (b) CM content 10%, (c) CM content 20%, and (d) CM content 30%.

Previous studies [66,67] refer to reduced cellulose crystallinity, lower lignin content, and increased surface area as crucial factors for increased glucose yield and a higher biogas production rate.

The relationship of cumulative biogas yield and VS removal rate was plotted in Fig. 4. Based on the data obtained in this study, a linear regression equation was established ($y = 0.0238x + 15.418$; $R^2 = 0.0427$). The VS removal rates correspond sufficiently with the biogas yield values and follow a similar trend.

3.5. Kinetic study results

Tables 4 and 5 summarize the results of a kinetic study using the first-order and cone models. Both models were found to have a good fit with the experimental data. The kinetic constants were calculated for 13 d of digestion time because the time needed for 80% biogas production (T_{80}) fell within the range of 6–22 d (Table 3). In the experiment, R1 showed the highest hydrolysis rates (K) of 0.3682 d^{-1} (based on the first-order model) and 0.4003 d^{-1} (based on the cone model). The reactors with 10% CM content (R2, R6, R10, and R14) showed sufficient hydrolysis rates that were similar to those of the reactors without CM (R1, R5, R9, and R13). One possible reason for the improved hydrolysis rates

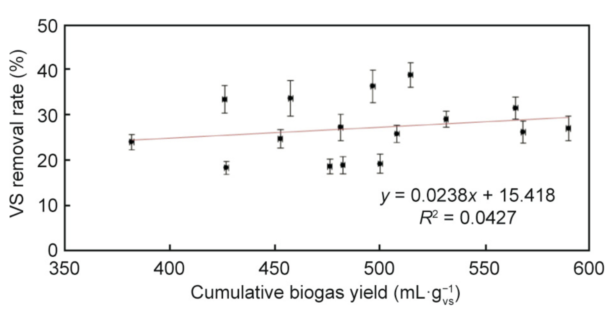

Fig. 4. Correlation of cumulative biogas yield and VS removal rate for all the experiments.

Table 4
Results of the kinetic study using the first-order model.

Reactor	K (d^{-1})	R^2	Biogas yield (mL·g$_{vs}^{-1}$)		Difference (%)
			Measured	Predicted	
R1	0.3682	0.9706	457.79	457.50	0.03
R2	0.3620	0.9603	514.87	514.62	0.04
R3	0.2086	0.8988	496.95	496.18	0.15
R4	0.2100	0.8673	426.43	425.47	0.22
R5	0.3023	0.9299	481.67	481.33	0.07
R6	0.2507	0.9562	531.83	531.46	0.07
R7	0.2292	0.8579	564.81	564.44	0.06
R8	0.2206	0.8462	382.27	381.48	0.21
R9	0.1964	0.9578	568.37	566.05	0.33
R10	0.2022	0.9972	452.99	452.13	0.19
R11	0.1122	0.9701	589.99	579.60	1.80
R12	0.0868	0.9869	508.35	491.14	3.40
R13	0.1456	0.9677	476.51	468.43	1.70
R14	0.1341	0.9845	427.29	420.60	1.60
R15	0.0678	0.9924	482.72	454.73	5.80
R16	0.0782	0.9900	500.42	480.15	4.10

Table 5
Results of the kinetic study using the cone model.

Reactor	K (d^{-1})	R^2	Biogas yield (mL·g$_{vs}^{-1}$)		Difference (%)
			Measured	Predicted	
R1	0.4003	0.9772	457.79	456.92	0.19
R2	0.3056	0.9633	514.87	512.02	0.55
R3	0.2892	0.9761	496.95	486.08	2.19
R4	0.2712	0.9562	426.43	415.81	2.49
R5	0.2983	0.9923	481.67	479.28	0.50
R6	0.2990	0.9782	531.83	526.96	0.92
R7	0.2827	0.9778	564.81	552.76	2.13
R8	0.3605	0.9824	382.27	374.92	1.92
R9	0.1454	0.9805	568.37	563.27	0.90
R10	0.2081	0.9878	452.99	449.19	0.84
R11	0.1280	0.9703	589.99	564.32	4.35
R12	0.1697	0.9728	508.35	471.36	7.28
R13	0.1403	0.9820	476.51	476.21	0.06
R14	0.1548	0.9757	427.29	421.04	1.46
R15	0.1076	0.9610	482.72	441.57	8.52
R16	0.1232	0.9656	500.42	465.92	6.89

of the substrates is that CM contains microbes that speed up the degradation of insoluble and complex particles. However, R4 and R8 showed significantly low biogas yields of 426.43 and 382.27 mL·g_{vs}^{-1}, respectively, as the methanogen growth was inhibited due to rapid BP acidification and a slow methanogenesis rate.

The K values decreased when the CM content was increased to 20% and 30%. Although the hydrolysis was slower, microbial interactions from the inoculum and manure favored the whole degradation performance. The fast acidification step may reduce the ammonia inhibition and further enhance the methanogenesis step. The difference between the measured and predicted values was low for the reactors with 10% or 0 CM content (Table 4). To evaluate the soundness of the model results in the first-order model and cone model, the predicted values for biogas production were plotted against the measured values (Fig. 5). The low values of the root mean square error (RMSE) reflect the model's high ability to accurately predict the bioactivities. The statistical indicators (R^2) are given in Tables 4 and 5 to provide a picture of the kinetics study.

According to the kinetics analysis, the kinetic parameters could be influenced by the process parameters. Therefore, the effects of these process parameters (i.e., the OL, CM content, and VS removal rate) on the kinetic parameters (G and K) were examined using a Pearson correlation analysis (Tables S1 and S2 in Supplementary data). In this case, the predicted biogas production potential (G) was significantly affected by the co-digestion ratio and the VS removal rate. The hydrolysis constant (K) showed low relevance to the process parameters and to the biogas production potential.

4. Conclusion

This study investigated the impact of OL and CM addition on the AD treatment of BPW. The overall results showed that the addition

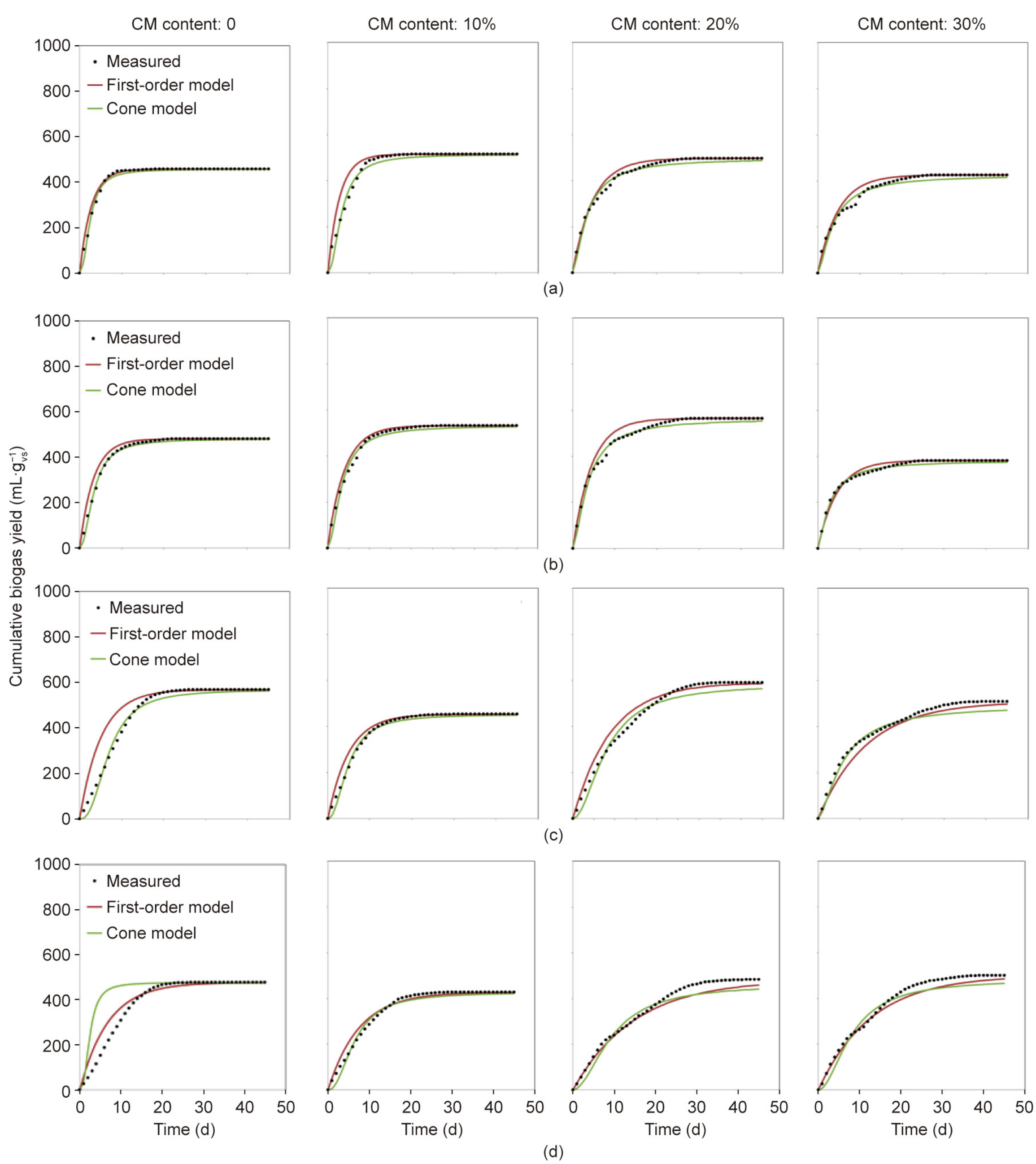

Fig. 5. Plots of measured and predicted cumulative biogas yields of BPs with four different CM contents and four different OLs: (a) 10 g_{vs}·L^{-1}, (b) 14 g_{vs}·L^{-1}, (c) 18 g_{vs}·L^{-1}, and (d) 22 g_{vs}·L^{-1}.

of CM to the BP treatment can reinforce the degradation performance. More specifically, an ISR of 2 resulted in the highest biogas yield and lowest technical digestion time in comparison with other ISRs, indicating that an appropriate amount of sludge is required for efficient operation. However, the daily biogas yield showed no clear interdependence with OL or CM content. In addition, a kinetic analysis using first-order and cone models showed that the kinetic parameters can be influenced by the process parameters. It is notable that pretreated BPs show good potential for enhanced biogas production and incremented energy output through co-digestion with CM, while providing a stable AD process.

Compliance with ethics guidelines

Spyridon Achinas, Janneke Krooneman, and Gerrit Jan Willem Euverink declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2018.11.036.

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