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IMPROVEMENT OF THE BIOCHEMICAL METHANE POTENTIAL OF FOOD WASTE BY MEANS OF ANAEROBIC CO-DIGESTION WITH SWINE MANURE

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Abstract - Food waste (FW) has potential for use by means of anaerobic digestion (AD). However, some characteristics of FW affect process stability and methane (CH_4) production. Using biochemical methane potential (BMP) tests, this study assessed the improvement of CH_4 production and hydrolysis of FW by means of anaerobic co-digestion (AcoD) with swine manure (SM). Different FW:SM ratios were studied under conditions with (WN) and without (NN) nutrients. The highest CH_4 production was obtained for the FW:SM 60:40 ratio in the WN and SN conditions with values of 72.87 and 62.83 mL CH_4 g VS^{-1}, respectively. This showed that AcoD of FW with SM presented synergistic effects, since increases of 27 (WN) and 13% (NN) were obtained in comparison with the mono-digestion of FW. There was also an improvement in the process stability (α index> 0.7), but there were no favorable effects with respect to the hydrolysis of FW.

Keywords: Anaerobic co-digestion; Food waste; Hydrolysis; Substrate ratios; Swine manure.

INTRODUCTION

According to the Food and Agriculture Organization of the United Nations (FAO), every year 1.3 billion tons of food waste (FW) are generated worldwide (FAO, 2011). Such FW represents the greatest component of municipal solid waste, accounting for 50% of the waste in developed countries and between 50-60% of the waste in developing countries (Thi *et al.,* 2015). FW is of special interest because more than 95% of such material ends up in dumps and landfills, where it is converted to materials with a high polluting potential (Schirmer *et al.,* 2014; Chen *et al.,* 2017). However, the high moisture content (70-90%) and organic matter of FW favor its use by means of anaerobic digestion (AD) (Zhang *et al.,* 2007; Sitorus *et al.,* 2013).

The AD of FW can affect methane (CH_4) production and the process stability due to acid pH, the lack of bicarbonate alkalinity, the accumulation of volatile fatty acids (VFAs) and the deficiency of some required nutrients, especially of metals such as nickel (Ni), cobalt (Co) and molybdenum (Mo), which are essential for the enzymes involved in CH_4 production (Facchin *et al.,* 2013). One of the strategies to improve these deficiencies in the AD of FW is anaerobic co-digestion (AcoD), which consists of mixing FW with other organic substrates that have complementary characteristics. The most used substrates in the AcoD of FW are domestic sewage sludge and agroindustrial wastes; these substrates include animal manure, particularly swine manure (SM) (Mata-Alvarez *et al.,* 2014), which increased generation is due to the growth of this economic sector (MacLeod et al., 2013).

Generally, SM is characterized by low Biochemical Methane Potential (BMP) and low C/N ratio, which can inhibit methanogenic archaea (Mata-Alvarez

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et al., 2014). However, it has high buffer capacity and nutrient content, which are complementary characteristics to FW. According to Tian *et al.* (2015) there are few studies that evaluate the AcoD of these two residues and additionally it is necessary to establish the most appropriate FW:SM ratio, that allows one to obtain synergic effects such as improvement in the stability of the process, greater CH_4 production, balance of nutrients and favorable effects on the hydrolysis, considered the limiting stage in the AD of these residues (Koch y Drewes, 2014). In light of the above, this study evaluated the AcoD as a strategy for the improvement of CH_4 production and the hydrolysis of FW by incorporating SM as a co-substrate.

MATERIALS AND METHODS

Characterization of Substrates and Inoculum

Substrates - FW was collected from the restaurant of the Universidad del Valle (Cali-Colombia), where approximately 2.4 tons of FW are generated on a weekly basis. The substrates were separated, considering the physical composition and the physicochemical characteristics of the unprocessed FW generated in a city that carries out source separation and selective collection (Oviedo-Ocaña *et al.,* 2017). The FW composition was 56% bananas and tubers, 24% citric fruits, 13% greens, legumes and vegetables and 7% non-citric fruits. Mechanical crushing of the FW was performed to obtain a particle size equal to or less than 10 mm, as recommended by Raposo *et al.* (2012). SM was obtained from a slaughterhouse in Valle de Cauca (Colombia). Both substrates were characterized according to the following parameters: moisture (%), pH (units), total alkalinity (TA) and bicarbonate alkalinity (BA) (g $CaCO_3$ L^{-1}), VFAs (g HAc L^{-1}), chemical oxygen demand (COD): total and filtered (g O_2 L^{-1}), total solids (TS) (g L^{-1}), volatile solids (VS) (g L^{-1}), total nitrogen (TN) (g L^{-1}), total phosphorus (TP) (g L^{-1}), nickel (Ni) (mg L^{-1}), cobalt (Co) (mg L^{-1}) and molybdenum (Mo) (mg L^{-1}) (ICONTEC, 2009; ICONTEC, 2011 and APHA *et al.,* 2012).

Inoculum - Sludge was collected from the anaerobic digester of a municipal wastewater treatment plant (WWTP), which operates with a complete mixture in the mesophilic range (35°C). The physicochemical characterization of the inoculum was carried out by means of pH, TA and BA, VFA, TS and VS measurements (APHA *et al.,* 2012). Additionally, the specific methanogenic activity (SMA) (g COD_{CH4} (g VSS d^{-1})) was determined, following the recommendations of Soto *et al.* (1993).

Description of the Biochemical Methane Potential tests

Experimental unit - The OxiTop® system (WTW, Giessen, Germany), based on the manometric method, was used in the Biochemical Methane Potential (BMP) tests. The working volume was 200 mL, whereas the free volume was 50 mL.

The OxiTop® system allows the direct measurement of the CH_4 generated by means of CO_2 sequestration. Here, 4 NaOH pellets were added to each reactor based on the results previously obtained. In this condition, chromatographic tests indicated that 99% of the biogas generated corresponded to CH_4 (Parra *et al*., 2015).

Experimental and Operational Conditions - BMP tests were performed in the mesophilic temperature range, thus ensuring a temperature of 35 ± 0.1°C inside the Thermostat cabinet TS 606-G/2-i (WTW, Giessen, Germany); pH was adjusted to 7 units using a sodium bicarbonate solution ($NaHCO_3$) (4%); agitation was manual and intermittent and was performed 3 times a day before measuring the pressure. The incubation period was 30 days, after which CH_4 production stabilized because the pressure did not vary by more than 5 hPa (Pabón *et al*., 2012).

A control (inoculum and distilled water) was included in all BMP tests to determine the CH_4 generated by the residual organic matter present in the inoculum and by endogenous metabolism, the value of which was subtracted from the CH_4 produced in each reactor. The control parameters that were measured at the end of each test were pH, TA and BA. Furthermore, the alpha index (α) that corresponded to the BA and TA ratio was calculated to analyze the stability of the process (Pérez and Torres, 2011). Additionally, the CH_4 volume under standard conditions was determined using the equations suggested by Parra *et al*. (2015).

BMP tests: Influence of the Substrate Ratio and Nutrient Addition

BMP tests were performed using a substrate/inoculum (S/I) ratio of 1 g $VS_{Substrate}$ /g $VS_{Inoculum}$, following the recommendations of Owen *et al.* (1979) and Labatut *et al*. (2011). The inoculum (I) concentration was 1.5 g VS L^{-1} (Soto *et al.,* 1993), whereas the VS concentrations of the substrates (S) were different from the ranges assessed in previous studies (Adelard *et al*., 2015; Tian *et al*., 2015). Each test was performed under conditions with (WN) and without (NN) nutrients. In the first case, the solution recommended by Aquino *et al.* (2007), Angelidaki *et al*. (2009) and Torres and Perez (2010) was added.

Table 1 shows the experimental design of the BMP tests, which were conducted in triplicate. The BMP for each substrate ratio in both nutrient conditions were

Table 1. BMP test to evaluate the influence of the substrate ratios and nutrient addition.

Reactor	FW		SM		I
	%	(g VS L^{-1})	%	(g VS L^{-1})	(g VS L^{-1})
1	100	1.50	0	0	1.50
2	80	1.20	20	0.30	1.50
3	60	0.90	40	0.60	1.50
4	50	0.75	50	0.75	1.50
5	40	0.60	60	0.90	1.50
6	20	0.30	80	1.20	1.50
7	0	0	100	1.50	1.50

compared in order to verify the possible contribution of these elements by the SM, determining the COD:N:P ratio and the concentration of trace elements essential for AD of RA such as Ni, Co and Mo (Uemura, 2010, Banks *et al.,* 2012, Facchin *et al.,* 2013).

In order to determine the possible synergistic or antagonistic effects of the substrate ratios assessed under WN and NN conditions, the difference between the experimental BMP (obtained from the substrate ratio and nutrient condition) and the weighted BMP (BMP_W) was calculated using Equation 1 (Labatut *et al.*, 2011). When the difference ($BMP- BMP_W$) was positive and higher than the value of the weighted BMP considering the standard deviations, a synergistic effect was noted; otherwise, the effect was antagonistic.

$$BMP_W = BMP_{FW} * \%FW + BMP_{SM} * \%SM \tag{1}$$

where BMP_W is the weighted biochemical methane potential, BMP_{FW} is the experimental biochemical methane potential obtained in the AD of FW (100:0 ratio), % FW is the FW percentage in the ratio, BMP_{SM} is the experimental biochemical methane potential obtained in the AD of SM (0:100 ratio), and % SM is the SM percentage in the ratio.

Influence of the Substrate Ratio and Nutrient Addition on Hydrolysis

The first-order kinetic model and modified Gompertz model were used (Equations 2 and 3, respectively). The first model assumes that the hydrolysis of the particulate matter follows first-order kinetics, whereas the second model is based on the premise that CH_4 production is proportional to microbial activity (Nielfa *et al.*, 2015; Parra-Orobio *et al.,* 2017).

$$BMP = BMP_{max}\left[1 - exp\left(-k_h t\right)\right] \tag{2}$$

$$BMP = BMP_{\max} \exp\left\{-\exp\left[\frac{R_{\max} e}{BMP_{\max}}\left(\lambda - t\right) + 1\right]\right\} \tag{3}$$

where BMP is the biochemical potential of the CH_4 accumulated during the test (mL CH_4 g VS^{-1}), BMP_{max} is the potential maximum CH_4 production when the time tends to infinity (mL CH_4 g VS^{-1}), k_h is the first-order hydrolysis constant (d^{-1}), t is the test time (d), R_{max} is the maximum rate of CH_4 production (mL CH_4 d^{-1} g VS^{-1}), λ is the lag phase (d), and *e* is the base of natural logarithm (*e* = 2.718).

For the estimation of the values in the first-order kinetic model equations (BMP_{max} and k_h) and the modified Gompertz model equations (BMP_{max}, R_{max} and λ), the experimental data of the mean BMP and the time for each reactor were used, for which a non-linear regression was obtained using the Levenberg-Marquardt algorithm in R software i386 3.4.2 (R Foundation®). To verify the adjustment of the data to the models, the coefficient of determination (R^2) and mean squared error (MSE) were determined, as recommended by Kafle and Kim (2013).

Statistical analysis - To assess the influence of the factors (substrate ratio and nutrient addition) on the response variable (BMP), analysis of variance (ANOVA) and Tukey's tests ($p<0.05$) were performed, using R software i386 3.4.2 (R Foundation®).

RESULTS AND DISCUSSION

Characterization of Substrates and Inoculum

Table 2 presents the results of the physicochemical characterization of the substrates and inoculum.

FW had a high moisture content because it was mainly composed of fruits and vegetables (Zhang *et al.*, 2007). Such waste degrades easily, thus favoring VFA formation and accumulation (Lü *et al.*, 2012; Sitorus *et al.*, 2013) with a value close to 4 g L^{-1}. According to Wang *et al.* (2009), this concentration can slightly inhibit the AD process. This value coincided with a low pH (5.17) and the absence of BA.

The values of COD_{Total}, TS, and VS coincide with those reported by Chu *et al.* (2008) and showed that FW contained a high organic matter content that was particulate, according to the value obtained for the $COD_{Filtered}/COD_{Total}$ ratio, which was 0.27. This can affect the hydrolysis stage of organic matter (Parra *et al.*, 2015). In terms of nutrient content, the COD_{Total}:N:P ratio (350:5.43:0.59) showed a phosphorus deficiency according to the value recommended by Ye *et al.* (2015) for the AD process (350:5:1). Low concentrations of Ni, Co and Mo are found, since these present the minimum values reported by Romero-Güiza *et al.* (2016) to be considered stimulants of the process.

In the case of SM, the pH, TA, BA and VFA values were similar to those reported by Ye *et al.* (2013) and Rodríguez-Verde *et al.* (2014). In general, the pH of SM was almost neutral, and unlike FW, BA accounted for approximately 60% of the TA, thus showing

Table 2. Physicochemical characterization of substrates and inoculum.

Parameter	Unit	*Food Waste (FW)	*Swine Manure (SM)	*Inoculum (I)
Moisture ($n_{FW, SM, I}=4$)	%	78.53 ± 6.18	84.62 ± 8.16	N.D
pH ($n_{FW, SM, I}=4$)	Units	5.17	7.34	7.16
TA ($n_{FW, SM, I}=4$)	g $CaCO_3$ L^{-1}	4.21 ± 3.44	21.06 ± 9.00	4.22 ± 0.83
BA ($n_{FW, SM, I}=4$)	g $CaCO_3$ L^{-1}	-	12.64 ± 2.42	2.42 ± 0.30
VFAs ($n_{FW, SM, I}=4$)	g HAc L^{-1}	3.65 ± 0.23	4.65 ± 0.81	1.54 ± 0.04
COD_{Total} ($n_{FW, SM}=4$)	g O_2 L^{-1}	80.41 ± 8.84	576.28 ± 29.57	N.D
$COD_{Filtered}$ ($n_{FW, SM}=4$)	g O_2 L^{-1}	22.03 ± 2.01	172.00 ± 2.36	N.D
TS ($n_{FW, SM, I}=4$)	g L^{-1}	88.31 ± 6.45	214.88 ± 0.46	56.98 ± 0.53
VS ($n_{FW, SM, I}=4$)	g L^{-1}	81.06 ± 6.95	174.55 ± 1.27	27.55 ± 0.21
TN ($n_{FW, SM}=4$)	g L^{-1}	1.25 ± 0.18	38.10 ± 0.20	N.D
TP ($n_{FW, SM}=4$)	g L^{-1}	0.14 ± 0.02	3.70 ± 1.49	N.D
Ni ($n_{FW}=3$); ($n_{SM}=1$)	mg L^{-1}	1.93 ± 1.42	3.14	N.D
Co ($n_{FW}=5$); ($n_{SM}=1$)	mg L^{-1}	1.63 ± 0.90	4.19	N.D
Mo ($n_{FW}=3$); ($n_{SM}=1$)	mg L^{-1}	0.33 ± 0.28	2.31	N.D
SMA	g COD_{CH4} (g VSS d)$^{-1}$	N.D	N.D	0.008

*Average values ± S.D (standard deviation); number of samples (n); N.D: not determined.

potential to contribute buffering capacity to the process. SM exhibited a high organic matter content, as shown by the values for COD_{Total}, TS and VS, which predominate in particulate form, in accordance with the $COD_{Filtered}/COD_{Total}$ ratio of 0.30. The COD_{Total}:N:P ratio (350:23.14:2.25) showed that these elements were not deficient. The concentrations of Ni, Co and Mo are in the ranges that favor the process and do not generate inhibition (Romero-Güiza *et al.* (2016).

With respect to the inoculum, the pH, TA, BA, VFA, TS and VS values were within the characteristic ranges for sludge from the anaerobic digesters of WWTPs (Raposo *et al.*, 2006; Cabbai *et al.*, 2013). Additionally, the pH value was near neutral, and the α index was 0.57, thus indicating that the inoculum contributed buffering capacity to the process. The VS/TS ratio (0.48) and the SMA value indicated a low activity of the inoculum compared to the findings of Angelidaki *et al.* (2009).

BMP tests: Influence of the Substrate Ratio and Nutrient Addition

Figure 1 compares BMP under WN and NN conditions for each FW:SM ratio assessed. Figure 1 shows that the BMP of FW (FW:SM 100:0 ratio) was higher than that of SM (FW:SM 0:100 ratio) under both nutrient conditions. This agrees with the findings of Browne *et al.* (2013) and Mata-Alvarez *et al.* (2014), who claim that SM presents a low organic content that affects CH_4 production. In general, BMP was higher under the WN condition.

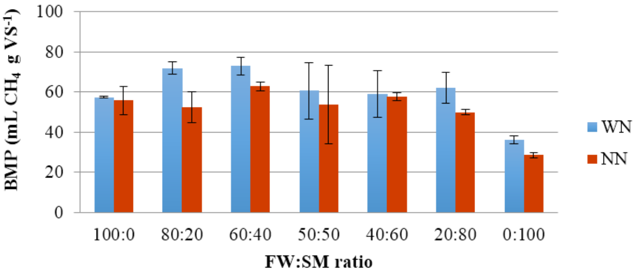

Figure 1. BMP for each substrate ratio and nutrient condition.

Under the WN condition, and according to the ANOVA and Tukey test ($p<0.05$) results, significant differences were found between the substrate ratio FW:SM 60:40 and the other ratios. Additionally, it was noted that the highest BMP values were obtained at the FW:SM 60:40 (72.87 mL CH_4 g VS^{-1}) and 80:20 (71.89 mL CH_4 g VS^{-1}) ratios. In general, a favorable effect of the AcoD was observed because, when considering the best ratio, a 27% increase in CH_4 production was obtained with respect to the AD of FW (100:0).

Under the NN condition, the FW:SM 60:40 ratio also presented the highest BMP value (62.83 mL CH_4 g VS^{-1}), which coincides with the values reported by Tian *et al.* (2015), who carried out an AcoD of SM and FW without nutrient addition and found higher CH_4 production at the ratios in which FW was present at a higher proportion. The ANOVA and Tukey test ($p<0.05$) results showed significant differences between different FW:SM ratios. In this regard, SM:FW 60:40 was the best ratio because it increased CH_4 production by 13% with respect to the AD of FW.

Additionally, the statistical analysis indicated that significant differences existed between the conditions assessed, with NN being the better of the two. To evaluate the effect of the evaluated factors on nutrient requirements, the concentrations of macro (COD ratio:N:P) and essential micronutrients (Ni, Co and Mo) in each FW:SM ratio under WN and NN conditions were determined, the results obtained are presented in Table 3.

Table 3 shows that FW (FW:SM 100:0 ratio) under the NN condition presented P deficiency, in contrast to the WN condition in which the COD:N:P ratio was higher than the recommended (350:5:1) (Ye *et al.*, 2015). However, there was a higher CH_4 production

Table 3. COD:N:P ratio and concentration of micronutrients for each FW:SM ratio under WN and NN conditions.

FW:SM	WN				NN			
Ratio	$\text{COD}_{\text{Total}}$:N:P	Ni	Co	Mo	$\text{COD}_{\text{Total}}$:N:P	Ni	Co	Mo
100:0	350: 15.52: 2.50	0.044	0.055	0.532	350: 5.43: 0.59	0.031	0.006	0.037
80:20	350: 20.74: 2.54	0.049	0.060	0.533	350: 15.33: 1.52	0.037	0.011	0.038
60:40	350: 22.66: 2.56	0.055	0.066	0.534	350: 18.96: 1.86	0.042	0.017	0.039
50:50	350: 23.23: 2.56	0.057	0.068	0.535	350: 20.03: 1.96	0.045	0.019	0.039
40:60	350: 23.66: 2.56	0.060	0.071	0.535	350: 20.85: 2.03	0.048	0.022	0.040
20:80	350: 24.27: 2.57	0.065	0.076	0.536	350: 22.00: 2.14	0.053	0.027	0.041
0:100	350: 24.68: 2.57	0.071	0.081	0.537	350: 22.78: 2.21	0.058	0.032	0.042

$\text{COD}_{\text{total}}$, N, P, Ni, Mo y Co (mg L^{-1}).

in the WN condition when the P value was higher than 2.50 mg L^{-1}. Regarding the content of N, at all FW:SM ratios, in both nutrient conditions, an adequate presence of this element was evidenced, so it is possible that the addition of macronutrients in AcoD of FW with SM is not required.

Regarding micronutrients, according to Moestedt *et al.* (2016) Ni is required for the synthesis of co-factor F430 involved in methanogenesis. The importance of Co is because it is a structural component of Vitamin B12 that catalyzes methanogenesis (Khanal, 2011) and Mo inhibits sulfatoreductora bacteria and is a co-factor of several enzymes (Matheri *et al.,* 2016). Table 3 shows that Ni concentrations were similar in both nutrient conditions and were close to the lower limit of the range reported as stimulant in the AD process (0.03 and 27 mg L^{-1}) (Romero-Güiza *et al.,* 2016). With respect to Co, at all FW:SM ratios evaluated in the NN condition, limitations of this element were present, because a concentration between 0.03 and 19 mg L^{-1} is required to favor the AD process (Romero-Güiza *et al.,* 2016). Finally, the concentrations of Mo in the NN condition have a stimulating effect (<0.05 mg L^{-1}), while in the WN condition do not present a risk of inhibition (Romero-Güiza *et al.,* 2016).

It has been reported that the addition of micronutrients is essential for AD of FW because these present low concentrations (Zhang *et al.,* 2012). In this sense, Facchin *et al.* (2013) showed that the external addition of micronutrients increased the BMP of FW by 60 to 70%. Additionally, the micronutrients contribution was made through the AcoD with other residues. Nordell *et al.* (2016) showed that, in the AcoD of FW with SM, the latter provides macro and micronutrients required in the process; however, the external addition of Ni and Co reduced the concentration of VFAs and increased the CH_4 production by 10%, which could be due to the low bioavailability of these micronutrients in the SM.

The stability of the process was determined by means of different control parameters shown in Table 4.

Table 4 shows that, under WN and NN conditions, the lowest α index was obtained in unmixed food waste (FW:SM 100:0 ratio), whereas in the AcoD with SM, the α index was higher than 0.60, indicating stable conditions between the degradation of organic matter and VFA consumption by acetogenic microorganisms (Campos, 2001; Labatut and Gooch, 2012). This behavior resulted from the fact that SM contributed bicarbonate alkalinity. This bicarbonate alkalinity provided buffering capacity, thus allowing continuous pH regulation and system recovery during the process (Flotats *et al*., 2001).

The existence of synergistic or antagonistic effects for each FW:SM ratio was verified under WN and NN conditions. The results are presented in Table 5.

Table 5 shows the synergistic effect of the AcoD of FW and SM, with the exception of the FW:SM 50:50 ratio under WN and NN conditions and the 80:20 ratio under the NN condition, where the effect is unclear, despite the difference between BMP and BMP_w being positive. This is because BMP_w was within the standard deviation of the BMP. Such an effect was also reported by Labatut *et al.* (2011), who indicated that, in this case, it was not possible to establish whether the effect was synergistic or antagonistic. In general, a favorable effect of the AcoD of FW with SM was observed. In

Table 4. Parameters measured after the process under WN and NN conditions.

FW:SM	WN				NN			
Ratio	pH	BA	TA	α index	pH	BA	TA	α index
100:0	8.45 ± 0.04	337.71 ± 5.23	1163.48 ± 31.37	0.29	8.24 ± 0.18	207.06 ± 24.40	414.12 ± 3.49	0.50
80:20	8.04 ± 0.03	369.75 ± 3.49	497.93 ± 3.49	0.74	8.32 ± 0.06	330.31 ± 34.86	475.75 ± 62.75	0.69
60:40	8.56 ± 0.23	438.77 ± 71.46	463.42 ± 10.46	0.95	7.95 ± 0.01	290.87 ± 22.66	401.80 ± 41.83	0.72
50:50	7.92 ± 0.02	313.06 ± 17.43	436.31 ± 1.74	0.72	7.60 ± 0.04	256.36 ± 17.43	337.71 ± 40.09	0.76
40:60	7.93 ± 0.16	303.20 ± 19.17	423.98 ± 27.89	0.72	7.81 ± 0.01	253.90 ± 34.86	367.29 ± 27.89	0.69
20:80	7.69 ± 0.02	266.22 ± 1.74	379.61 ± 3.49	0.70	7.62 ± 0.06	224.32 ± 3.49	337.71 ± 1.74	0.66
0:100	7.44 ± 0.01	189.81 ± 5.23	285.94 ± 3.49	0.66	7.43 ± 0.02	197.20 ± 15.69	340.17 ± 13.94	0.58

pH (Unit); BA and TA (mg $CaCO_3$ L^{-1}); number of assays: 3.

Table 5. Synergistic or antagonistic effects of the FW:SM ratio on BMP under WN and NN conditions.

FW:SM ratio	WN					NN				
				Effect					Effect	
	BMP	S.D	BMP_W	$BMP-BMP_W$		BMP	S.D	BMP_W	$BMP-BMP_W$	
100:0	57.33	0.35	57.33	0.00	-	55.83	7.08	55.83	0.00	-
80:20	71.89	3.22	53.10	18.79	S	52.46	7.82	50.39	2.06	*
60:40	72.87	4.37	48.87	24.00	S	62.83	2.12	44.95	17.87	S
50:50	60.64	14.08	46.76	13.88	*	53.69	19.34	42.23	11.46	*
40:60	58.89	11.74	44.65	14.25	S	57.50	1.95	39.51	17.99	S
20:80	62.08	7.82	40.42	21.66	S	49.93	1.28	34.07	15.86	S
0:100	36.19	2.07	36.19	0.00	-	28.63	1.27	28.63	0.00	-

BMP_W: weighted biochemical methane potential (mL CH_4 g VS^{-1}); S.D: standard deviation; S: synergistic effect; *: undefined; number of assays: 3.

this sense, the AcoD improved the AD of FW because it contributed important nutrients such as nitrogen and phosphorus for the growth of microorganisms. Furthermore, it contributed buffering capacity to the process by maintaining a stable pH (Kafle and Kim, 2013; Adelard *et al*., 2015; Lima *et al*., 2016).

Influence of the Substrate Ratio and Nutrient Addition on Hydrolysis

Figure 2 and 3 show the graphs with the experimental data and adjusted models under WN and NN conditions, respectively.

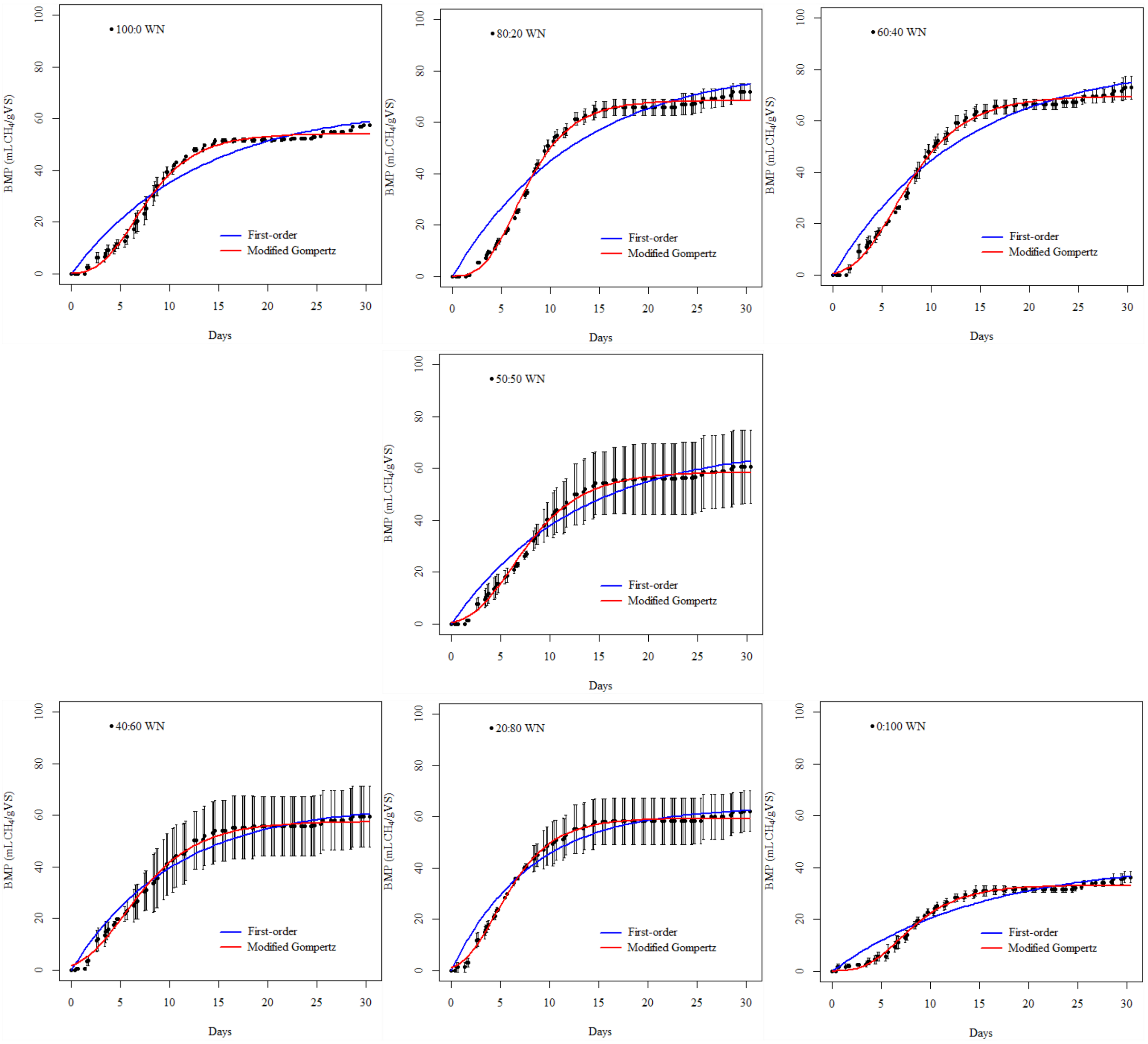

Figure 2. BMP and adjusted First-order and Modified Gompertz models under the WN condition.

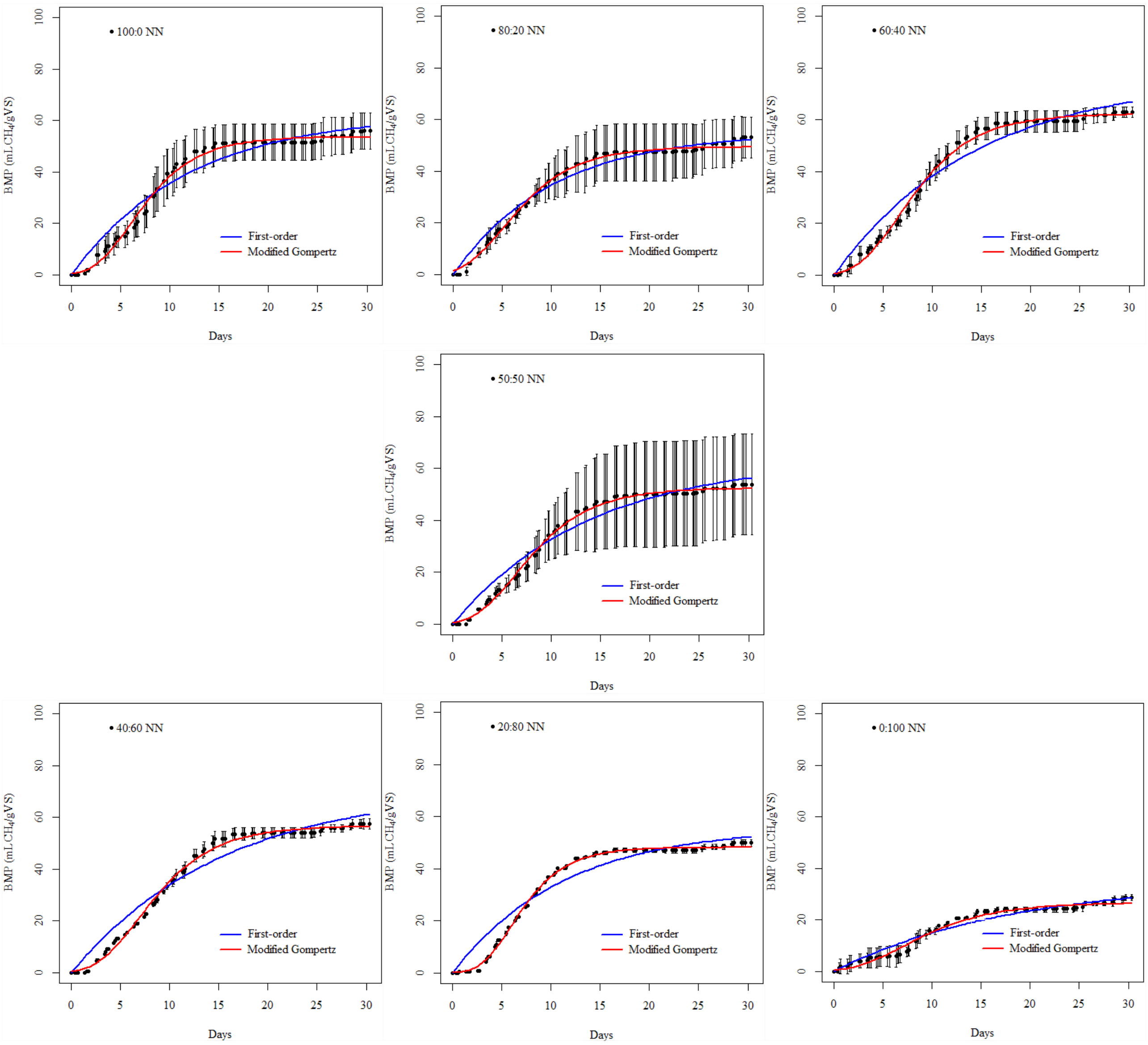

Figure 3. BMP and adjusted First-order and Modified Gompertz models under the NN condition.

Figures 2 and 3 show that, for both nutrient conditions (WN and NN), the experimental results presented a better adjustment to the modified Gompertz model because this model takes into account the lag phase that was observed in all BMP curves. On the contrary, the first-order kinetic model was not precise in the representation of the process. However, according to Pagés *et al.* (2011), the first-order kinetic model provides a useful description of the rate of degradation and the maximum CH_4 production.

Tables 6 and 7 show the respective results of the kinetic parameters determined using the first-order and modified Gompertz models for each FW:SM ratio assessed under WN and NN conditions.

Table 6. Kinetic parameters for FW:SM ratios under the WN condition.

FW:SM ratio	First-order Kinetics Model				Modified Gompertz Model				
	BMP_{max}	**k_h (d^{-1})**	**R^2**	**MSE**	**BMP_{max}**	**R_{max}**	**λ (d)**	**R^2**	**MSE**
100:0	64.98 ± 2.35	0.078 ± 0.006	0.937	23.04	54.06 ± 0.28	5.80 ± 0.15	2.85 ± 0.12	0.993	2.56
80:20	82.54 ± 3.14	0.078 ± 0.007	0.931	42.12	68.43 ± 0.28	7.92 ± 0.17	3.12 ± 0.09	0.995	2.76
60:40	82.94 ± 2.52	0.077 ± 0.005	0.955	25.54	69.46 ± 0.31	6.48 ± 0.12	2.22 ± 0.10	0.995	2.58
50:50	69.10 ± 1.99	0.079 ± 0.005	0.956	17.54	58.50 ± 0.27	5.44 ± 0.11	2.10 ± 0.11	0.995	2.01
40:60	64.05 ± 1.13	0.096 ± 0.004	0.971	9.96	57.51 ± 0.28	5.10 ± 0.11	1.13 ± 0.12	0.994	2.14
20:80	63.82 ± 0.88	0.125 ± 0.005	0.967	11.76	59.32 ± 0.17	6.78 ± 0.11	1.25 ± 0.07	0.997	1.13
0:100	42.45 ± 2.02	0.066 ± 0.006	0.933	9.71	33.10 ± 0.20	3.54 ± 0.10	3.33 ± 0.14	0.991	1.27

BMP_{max} (mL CH_4 g VS^{-1}); R_{max} (mL CH_4 d^{-1} g VS^{-1}).

Table 7. Kinetic parameters for FW:SM ratios under the NN condition.

FW:SM Ratio	First-order Kinetics Model				Modified Gompertz Model				
	BMP_{max}	k_h (d^{-1})	R^2	MSE	BMP_{max}	R_{max}	λ (d)	R^2	MSE
100:0	62.46 ± 1.89	0.084 ± 0.006	0.945	18.90	53.63 ± 0.32	5.35 ± 0.15	2.28 ± 0.14	0.991	3.12
80:20	54.84 ± 0.88	0.099 ± 0.004	0.974	6.62	49.38 ± 0.25	4.49 ± 0.10	1.06 ± 0.12	0.993	1.79
60:40	76.10 ± 2.75	0.070 ± 0.005	0.952	22.09	62.17 ± 0.32	5.43 ± 0.11	2.36 ± 0.12	0.995	2.44
50:50	63.57 ± 2.08	0.072 ± 0.005	0.957	13.92	52.38 ± 0.24	4.60 ± 0.08	2.21 ± 0.10	0.996	1.36
40:60	71.32 ± 2.97	0.064 ± 0.005	0.950	19.83	56.62 ± 0.30	4.90 ± 0.10	2.58 ± 0.12	0.995	2.08
20:80	56.12 ± 1.80	0.088 ± 0.007	0.933	19.72	48.15 ± 0.14	5.74 ± 0.09	2.81 ± 0.07	0.997	0.73
0:100	34.85 ± 1.65	0.056 ± 0.005	0.952	3.84	26.54 ± 0.31	1.95 ± 0.07	2.04 ± 0.24	0.980	1.58

BMP_{max} (mL CH_4 g VS^{-1}); R_{max} (mL CH_4 d^{-1} g VS^{-1}).

Tables 6 and 7 show that for both nutrient conditions (WN and NN), the values of R^2 and MSE indicated a better adjustment to the modified Gompertz model (R^2 >0.98 and MSE< 8). Additionally, it was noted that the hydrolysis constant (k_h) of FW was higher than that of SM. Therefore, the incorporation of SM did not produce an increase in the value of k_h or a reduction in λ. This may be due to the presence of lignocellulosic matter in SM, known by its slow degradation (Pavlostathis and Giraldo-Gomez, 1991). In addition, the lower degradation rate of SM can be related to the predominance of particulate organic matter. This is consistent with the findings of Bouallagui *et al*. (2005), who indicated there is an inversely proportional relationship between the degradation rate of the substrates and their particulate organic matter content.

CONCLUSIONS

FW has a potential for use by means of AD, given the high organic matter and moisture content of the waste. However, the low pH of FW, the lack of bicarbonate alkalinity and its phosphorus deficiency affect CH_4 production and the stability of the process. One strategy to improve such deficiencies in AD of FW is the AcoD with waste that has complementary characteristics, such as SM, which can provide phosphorus and buffering capacity of the process.

The AcoD of FW with SM improved the BMP of FW; the highest value was obtained for the FW:SM 60:40 ratio under the WN condition (72.87 mL CH_4 g VS^{-1}). This represented a 27% increase in BMP in comparison with the AD of the unmixed FW. In general, the BMP was higher under the WN condition and presented synergistic effects that were observed by the increase in CH_4 production, the contribution of phosphorus and essential micronutrients and the improvement of the stability of the process.

The experimental results showed better adjustment to the modified Gompertz model, which took the lag phase (λ) into consideration. In this study, the addition of SM to FW did not favor hydrolysis because this did not cause an increase in the rate of degradation (k_h) or a reduction in the lag phase in comparison with the AD of the unmixed FW.

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NOMENCLATURE

α index	Alpha index (BA/TA)
λ	Lag phase
AD	Anaerobic digestion
AcoD	Anaerobic co-digestion
BA	Bicarbonate alkalinity
BMP	Biochemical Methane Potential
BMP_W	Weighted Biochemical Methane Potential
FW	Food Waste
k_h	First-order hydrolysis constant
MSE	Mean squared error
NN	Without nutrients
S.D.	Standard deviation
SM	Swine manure
TA	Total alkalinity
WN	With nutrients
WWTP	Wastewater treatment plant

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