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Evaluation of the effect of the application of combined pretreatments and inoculum with high alkalinity on food residues through BMP tests.

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Abstract

The management and control of food waste is currently seen as a growing concern, anaerobic digestion is a promising alternative for the valorization of food waste. This study evaluates the effect of the application of three pretreatments (grinding, pH control, thermal treatment) and organic load control, employing a high alkalinity inoculum for methane production through BMP tests, using a Taguchi L₈ experimental design of 4 factors and 2 levels, resulting in the best performance (65.91 NmL · g⁻¹ TVS) with pretreatment conditions of grinding with fine particle size, pH 11, thermal pretreatment at 60 °C and a concentration of 14 g TVS · L⁻¹, which represents an improvement of 34.66% in comparison with the food waste without pretreatments.

Keywords: Food waste, Anaerobic Digestion, Methane, Renewable energy

1 Introduction

At present, climate change has become a problem on a global scale. Increased temperature, changes in rainfall cycles, modifications in crops cycles, and increased drought periods are some of the results of climate change [1–3]. The main cause of climate change is the accumulation of greenhouse gases (GHG) in the atmosphere, and one of the anthropogenic sources is the organic fraction of municipal solid waste, when it degrades in landfills by anaerobic microorganisms, it produces liquid (leachates) and gaseous pollutants (CO₂,

CH₄ y H₂S). When released into the environment, these pollutants contribute to aquifer contamination and increase the concentration of greenhouse gases (GHG) [1, 2]. According to the 2021 Food waste index report, 8 to 10 percent of the GHG generated globally is related to food that was not consumed. By 2019, out of the 931 million tons of food waste generated globally, it is estimated that 26 percent (244 million tons) come from the foodservice industry, the remaining 74 percent is divided between household and retail waste. As a result, food waste generated by the food industry [5] has become an emerging problem in recent

decades. The main components of food waste include carbohydrates, proteins, lipids, and trace inorganic components [6–8], which can be used for energy production by anaerobic processes. The biodegradability of a substrate is the main factor to know if waste biomass is eligible for anaerobic processes, which depends on its physicochemical characteristics and its composition[9]. One of the main problems encountered in the anaerobic digestion process is the destabilization of the system due to acidification, accumulation of ammonium, oils, fats, and salts, which can lead to a decrease in the process efficiency and even inhibit it [10]. The application of pretreatments to food waste has proven to be a process that generally helps improve the degradability and stability of the anaerobic process [11–13]. Based on the above, it is necessary to develop advances in the existing processes to increase the consumption of OFMSW through combined pretreatments and inoculum with high alkalinity. The combined application of pretreatments pursues the following objectives: increase in the surface area and solubilization of simple compounds by particle size reduction [14–16]; adjustment of pH and transformation of organic compounds by addition of strong acids or alkalis or oxidant agents [15] depending on the nature of the residue [16]; control of the concentration of the reactor feed [17, 18]. Biochemical methane potential test (BMP) tests have become important in the search for the improvement of methane and hydrogen production from waste[13, 19] because it allows the obtention of optimal conditions that influence the anaerobic digestion process in a relatively short time[19, 20]. By using this method, several factors that affect the quality of biogas can be tested, such as the substrate-inoculum (S/I) ratio, pH, temperature, etc. [21].

Anaerobic inoculum

The anaerobic inoculum used for the BMP test is an important factor for the correct development of the test. The amount of macronutrients and trace elements is an important characteristic which has an impact on the performance of the system, and also affects the methane production.[22]

This study aims to evaluate the application of the combined pretreatment process and concentration control on the production of methane generated from the catering industry waste through

BMP tests, employing an inoculum with high alkalinity content (higher than 50 g CaCO₃ ·L⁻¹).

2 Materials and methods

2.1 Food waste

Food waste (substrate) was obtained from a restaurant located at coordinates (19°42′23.7″N 101°10′25.3″W) that specializes in fish and seafood. The waste collection process was carried out by collecting three 2.6 L samples during a 10 h work period, then they were blended to obtain a representative sample of the waste generated. The residues were preserved at 4 °C for 24 h before being processed and their characterization was accomplished according to parameters and methods established in Table 1.

2.2 Inoculum

The inoculum used for the test was obtained from an anaerobic reactor for wastewater treatment, located in the city of Morelia, Michoacán at coordinates (19°40′32.8″N 101°12′58.5″W), which was subjected to an enrichment process using a pig manure suspension (8% total solids) for 45 days [23]. This suspension was mixed with CaO at a rate of 2 g CaO ·L⁻¹ of suspension to improve the characteristics of the inoculum (total alkalinity, alpha ratio); the inoculum was fed with this suspension every 7 days. Once the inoculum was enriched, it was sieved (Tyler mesh No. 18) to remove inert matter present in the mixture.

2.3 Experimental design and pretreatment process

The experimental design implemented was a Taguchi L₈ orthogonal arrangement (Table 2), which contemplates four factors: three pretreatments and feed concentration control, with two levels, as shown in Table 2, obtaining a total of 8 experimental conditions (Table 3). Additionally, an inoculum blank was considered, as well as two residue blanks (one for each of the feed concentrations). Each of the tests was carried out in duplicate, giving a total of 22 experimental units (EU).

Type I grinding was performed in an Oster® blender model BLSTUG6648B-013, and type II, in a manual disc mill with an opening of 6 mm.

Table 1 Characterization tests for inoculum and residue.

Parameter	Units	Method/Norm	Inoculum	Waste
pH	N/A	APHA	X	X
Conductivity	mS·cm ⁻¹	APHA	X	X
Alkanity	mg CaCO ₃ ·L ⁻¹	APHA	X	X
Solids	mg·L ⁻¹	APHA	X	X
COD ^a	mg·L ⁻¹	Method 8000 HACH	X	X
Total Nitrogen	mg·L ⁻¹	Method 10242 HACH	X	X
Total Phosphorus	mg·L ⁻¹	Method 10127 HACH	X	X
C, H, O, N, S	%	LECO's Method	X	X
Humidity	%	Gravimetric		X
Alpha ratio	N/A	Volumetric	X	

^aChemical Oxygen Demand**Table 2** Taguchi experimental design for the BMP test.

Factor	Level	
	Low	High
Concentration (g TVS ·L ⁻¹)	7	14
Mechanic (Type)	I	II
Chemical (pH)	6.5	11
Thermal (°C)	25	60

The chemical pretreatment consisted of controlling the pH at 6.5 and 11, implementing CaO. The thermal pretreatment was performed with an electrical resistance (1000 W, Pretul) to adjust the temperature of the dilution water to 25 °C and 60 °C. The concentration adjustment to 7 g TVS ·L⁻¹ and 14 g TVS ·L⁻¹, respectively, was carried out simultaneously with the thermal treatment.

2.4 Biochemical methane potential test (BMP)

The model for the test was an adaptation of the reaction system proposed by Cabbai *et al.* [24] and its construction consist of a 500 mL Kimax[®] screw cap glass bottle (working volume 400 mL) (Fig. 1). The cap was modified by incorporating a 4 mm diameter outlet connector, which was connected to a displacement quantification system for the biogas produced. The biogas storage vessel was made of polypropylene with a capacity of 1000 mL, for which two 4 mm diameter conduits were adapted for the flow of gas and water from the

system. The EU consisted of a mixture of 50% enriched inoculum and 50 % pretreated residue (1:1 volume), which were then placed in a Daihan Lab Tech[®] model LSI-1005R incubator with a temperature control of 35 °C ± 0.5 and 60 rpm for 32 days[25].

Fig. 1 Schematic diagram of BMP system construction.

The collected gas was analyzed by gas chromatography in a Buck Scientific[®] gas chromatograph, model 910 GC with thermal conductivity detector (TDC) and 1-meter-long silica ss column with an external diameter of 3.17 mm and finger-tight junction.

Table 3 Matrix of operation conditions for each EU.

EU	Grinding	pH	Temperature (°C)	Concentration (g TVS · L ⁻¹)
1	Blender (type 1)	11	60	14
2	Blender (type 1)	11	25	7
3	Grinder (type 2)	6.5	60	14
4	Grinder (type 2)	6.5	25	7
5	Blender (type 1)	6.5	60	7
6	Blender (type 1)	6.5	25	14
7	Grinder (type 2)	11	60	7
8	Grinder (type 2)	11	25	14
9	Inoculum			
10	Inoculum/waste 7 g TVS · L ⁻¹			
11	Inoculum/waste 14 g TVS · L ⁻¹			

2.5 Analytical methods

The parameters (pH, conductivity, alkalinity, total solids, and volatile solids) were analyzed according to Standard Methods [26]; the chemical oxygen demand, total nitrogen, and total phosphorus were determined through HACH methodology; the alpha ratio was analyzed according to the methodology presented by Li *et al.* [27]. The elemental analysis (C, H, N, S) was determined with a LECO[®] equipment model CHN628 with external sulfur module. After 32 days, the EU was disassembled, and the content was analyzed according to Table 4. Main effects plots were carried out in Minitab 17[®].

2.6 Kinetic constant

The first-order model (Eq. 1) describes methane production in BMP tests. $B(t)$ represents the methane concentration in function of time, t is the independent variable (time), B is the final methane production in the system, and k is the kinetic constant of methane production [28].

$$B(t) = B(1 + e^{-kt}) \quad (1)$$

$$\left(\frac{\ln(-\frac{B(t)}{B} + 1)}{-t} \right) = k \quad (2)$$

The first-order model (Eq. 3) describes the consumption of volatile solids in BMP tests. Ca represents the concentration of volatile solids over a period of time, t is the independent variable (time), Ca_0 is the initial concentration of volatile

solids in the system, and is the degradation kinetic parameter [29].

$$Ca = Ca_0 e^{-kt} \quad (3)$$

$$\left(\frac{\ln(\frac{Ca}{Ca_0})}{-t} \right) = k \quad (4)$$

3 Results and Discussion

3.1 Characterization of residue and inoculum

The results from the food waste characterization and the inoculum are shown in Table 4. It can be observed that the inoculum presents the desirable characteristics for anaerobic processes [8, 30]: pH 7.16 ± 0.01 , an Alpha ratio higher than 0.5, TS concentration of 63 ± 13.01 g TS · L⁻¹ and conductivity of 11.04 ± 0.01 mS · cm⁻¹, regarding the residue, it presented an acid pH with a value of 4.01 ± 0.01 , TVS concentration of 168.61 ± 18.46 g TVS · L⁻¹, which represents 96.83 % of organic matter based on total solids [31].

The results of the waste elemental analysis are shown in Table 5, from which the C:N:P ratio of 46.5:7.4:1 was obtained, which is considered to present a minor nitrogen deficiency for carbon removal for the anaerobic processes [32]. This does not limit the anaerobic process operation.

3.2 BMP test

The initial pH of the UE was found to be within the recommended values for anaerobic processes

Table 4 Initial characterization of inoculum and residue.

Parameter	Units	Inoculum	Waste
pH	N/A	7.16 ± 0.01	4.01 ± 0.01
Conductivity	$\text{mS} \cdot \text{cm}^{-1}$	11.04 ± 0.01	11.27 ± 1.58
Total Nitrogen	$\text{g} \cdot \text{L}^{-1}$	1.39 ± 0.06	0.50 ± 0.14
Total Phosphorus	$\text{g} \cdot \text{L}^{-1}$	2.20 ± 0.30	1.06 ± 0.08
COD ^a	$\text{g} \cdot \text{L}^{-1}$	63.20 ± 13.01	187.20 ± 31.68
Solids	$\text{g} \cdot \text{L}^{-1}$	63.00 ± 0.31	174.12 ± 17.20
Solids	$\text{g} \cdot \text{L}^{-1}$	44.65 ± 0.35	168.61 ± 18.46
Solids	$\text{g} \cdot \text{L}^{-1}$	10.10 ± 11.62	25.21 ± 1.26
Alkanity	$\text{g CaCO}_3 \cdot \text{L}^{-1}$	52.16 ± 1.19	N/D
Alpha ratio	N/A	0.63 ± 0.02	N/D

^aChemical Oxygen Demand**Table 5** Elemental analysis of food waste.

Parameter	Weight percentage
C	52.56 ± 0.640
H	8.00 ± 0.130
N	8.37 ± 0.260
O	29.00 ± 0.42
P	1.13 ± 0.015

(7-8.5) [33]. This can be attributed to the inoculum's initial conditions (alpha ratio 0.63, total alkalinity $52.6 \text{ g CaCO}_3 \cdot \text{L}^{-1}$). The buffer conditions present in the inoculum helped to compensate for the acidic nature of the residue, thus maintaining an adequate pH for the degradation process.

Generally, the pH presented a decay in all the EU (Table 6). Because of the synthesis of volatile fatty acids (VFA) during anaerobic digestion, this behavior is considered typical.[27]; despite these acids, the pH remained within the recommended range. This can be attributed to the alpha ratio, the total alkalinity of the inoculum, and the CaO added in the pretreatments, which helped improve the pH of the waste and to maintain the digestion conditions due to the neutralization of the acid character of the waste, as well as the acids that were formed in the degradation process. Table 6 shows the alpha ratio values at the end of the test. Most of the EU, except for EU 7, 8, and 9 (inoculum blank), present values below 0.5, indicating the consumption of buffer capacity within the system; the total alkalinity (Table 6) in all the

systems presented a low value compared to the recommended levels ($13 - 15 \text{ g CaCO}_3 \cdot \text{L}^{-1}$) [33]. The electrical conductivity was found to be within normal values for anaerobic processes [34, 35]. It is possible to distinguish two groups: those with values below $8 \text{ mS} \cdot \text{cm}^{-1}$ (concentration of $7 \text{ g TVS} \cdot \text{L}^{-1}$) and those with values above $8 \text{ mS} \cdot \text{cm}^{-1}$ (Concentration of $14 \text{ g TVS} \cdot \text{L}^{-1}$), indicating that the fed concentration has a direct effect on the electrical conductivity, which may be associated with the salts and seasoning implemented during the cooking processes of the food [36]. The electrical conductivity can also be considered as an estimate of the salinity of the system, according to De Vrieze *et al.* [37]. To avoid salinity stress, values should be kept below $30 \text{ mS} \cdot \text{cm}^{-1}$, so conductivity was kept below these values (Table 6).

3.3 Biogas production

The BMP test was performed over 32 days [25]. Fig. 2 shows the accumulated daily biogas production of the EU. It is observed that the highest biogas production in the different EU occurred in the units fed with an organic load of $14 \text{ g TVS} \cdot \text{L}^{-1}$, with productions higher than 800 NmL of biogas; on the other hand, the EU with an organic load of $7 \text{ g TVS} \cdot \text{L}^{-1}$ presented a production between 540 and 765 NmL of biogas. EU 9 (inoculum blank) did not show any biogas production. According to Jiang *et al.* [38] and Park *et al.* [39], the amount of available feed is a key factor for the maintenance of optimal conditions for the anaerobic process and biogas production. This segmentation

Table 6 Characterization of EU.

EU	Initial pH	Final pH	Initial Conductivity	Final Conductivity	Final Total Alkalinity	Final Alpha ratio
1	8.28 ± 0.06	7.11 ± 0.07	8.39 ± 0.19	7.97 ± 0.20	5225.00 ± 705.34	0.30 ± 0.03
2	8.13 ± 0.01	7.14 ± 0.01	7.36 ± 0.2	6.76 ± 0.13	5153.75 ± 570.99	0.32 ± 0.02
3	7.50 ± 0.03	7.05 ± 0.04	8.84 ± 0.21	7.37 ± 0.21	4465.00 ± 235.11	0.38 ± 0.06
4	7.47 ± 0.03	7.01 ± 0.05	7.58 ± 0.28	6.19 ± 0.26	4441.25 ± 335.88	0.31 ± 0.01
5	7.41 ± 0.01	6.99 ± 0.02	7.93 ± 0.03	6.53 ± 0.11	4203.75 ± 167.94	0.34 ± 0.01
6	7.44 ± 0.01	7.04 ± 0.07	8.67 ± 0.01	7.80 ± 0.12	4180.00 ± 134.35	0.38 ± 0.01
7	7.81 ± 0.08	7.14 ± 0.02	7.40 ± 0.05	6.35 ± 0.19	4156.25 ± 268.70	0.60 ± 0.05
8	8.44 ± 0.07	7.15 ± 0.02	8.45 ± 0.14	7.41 ± 0.38	3942.50 ± 201.53	0.57 ± 0.02
9	7.47 ± 0.02	7.20 ± 0.01	6.50 ± 0.09	4.99 ± 0.09	3657.50 ± 268.7	0.51 ± 0.01
10	7.03 ± 0.06	6.98 ± 0.01	7.80 ± 0.01	6.28 ± 0.05	3420.00 ± 134.35	0.47 ± 0.02
11	6.88 ± 0.02	6.81 ± 0.01	8.89 ± 0.01	7.37 ± 0.21	3420.00 ± 134.35	0.35 ± 0.05

into two groups regarding the organic load presented a normal development for the conditions in which the degradation process was carried out.

Fig. 2 Cumulative biogas production.

Fig. 3 presents the results of the main effects analysis, which indicate that grinding with a processor and the concentration of 14 g TVS · L⁻¹ are the most important factors for biogas production, followed by the chemical treatment, pH 11 and the temperature of 60°C, which had the least effect on biogas production.

Fig. 3 Main effects plot for the signal-to-noise factor for cumulative biogas volume.

3.4 Biogas composition

Fig. 4 presents the composition from the biogas obtained in all the EU by chromatographic analysis. In general, it is observed that most of the

EU presented a biogas production with a composition higher than 60 % CH₄, except for EU 3, 6, 8, and 11, which presented methane concentration lower than 50 % v/v. Those units were the ones fed with a concentration of 14 g TVS · L⁻¹. Another recurrent factor in this group were the low pH conditions (6.5), therefore, low methane concentration is associated with low pH operating conditions; Fig. 5 shows the main effects graph for methane percentage, which indicates that a fed concentration of 14 g TVS · L⁻¹ and low pH conditions (6.5) has a minor effect on the increase of methane concentration. When CaO comes in contact with water, through the hydration reaction, CaO is transformed to Ca(OH)₂ (Eq. 3), and when dissolved into the system, according to Sebola *et al.* [40], it functions as a caustic solvent that captures the CO₂ present in the water (eq. 4). Likewise, when Ca(OH)₂ comes in contact with H₂S it generates the formation of sulfur salts (Eq. 5) [41]; therefore, it is possible to affirm that the Ca(OH)₂ present in the system helps with the biogas upgrading process. This can be observed through the EUs with chemical treatment and a pH 11, which are the ones that presented a low CO₂ composition according to the corresponding fed concentration. As an example, we can take EU 1 which presents a methane concentration higher than 60 % v/v, despite having a fed concentration of 14 g TVS · L⁻¹.

The EU with a feed concentration of 14 g TVS · L⁻¹ presented a higher methane production. This is explained based on the amount of organic matter available for consumption. When organic matter is degraded, it's transformed into VFA, which are later consumed to carry out the formation of CH₄, CO₂, and H₂. As mentioned before, the segregation into two groups according to the volume of biogas produced is directly related to the organic matter workload: the greater the amount of food available the greater the CH₄, CO₂, and H₂ generation. Remembering that the Ca(OH)₂ present in the solution works as a caustic solvent that allows the capture of acid products

Fig. 4 Composition of biogas in the EU.

Fig. 5 Main effects plot for the SN factor biogas methane percentage.

such as CO₂, and H₂S, this improves the quality of the biogas by increasing the concentration of CH₄. As the volume of CO₂ increases, the consumption of Ca(OH)₂ as a caustic solvent to retain this gas increases. As its consumption increases, it loses efficiency in CO₂ capture, as a result when working with high feed concentrations it is possible to expect that CO₂ production will be higher, and at lower feed concentrations the retention of the CO₂ in the system will improve and the quality of the biogas generated will increase. On the other hand, EU 6 presented the highest CO₂ production, followed by EU 11 and 3, all with a concentration above 50 %; the same EU correspond to a pretreatment of pH 6.5 which evidences that the addition of CaO to the system confers the conditions to capture part of the CO₂ generated in the anaerobic processes [40].

3.5 Cumulative methane production

Fig. 6 shows the cumulative production volumes of biogas, CH₄, and CO₂ obtained in the EU. The EU that presented the best CH₄ production was EU 1 (646 NmL) followed by EU 11, 2, 6, 8, and 5. EU 1, 6, 8, and 11 correspond to the feed concentration of 14 g TVS · L⁻¹, and EU 1, 2, 5, and 6 are consistent with a type I (blender) mechanical pretreatment; based on this, it is considered that feed concentration and grinding type are key factors in CH₄ production; grinding with a blender improves the solubilization processes of organic matter, and combined with a high organic load, indicates that the amount of organic matter readily available is key for CH₄ production [42], therefore the amount of organic matter readily available is a key factor for CH₄ production.

Fig. 6 Final production of Biogas, methane, and carbon dioxide in the EUs.

Subsequently, the main effects graph for CH₄ production (Fig. 7) indicates that grinding and concentration are the factors that have the greatest effect on the increase of CH₄ production; in the case of grinding, it is shown that doing so with a blender has the greatest effect on CH₄ production. Regarding feed concentration, it is indicated that a concentration of 14 g SSV · L⁻¹ presents the best effect in the increase of CH₄ production for this case.

3.6 Methane yield

Fig. 8 shows the obtained yields of CH₄ and CO₂. In the case of CH₄ production, the EU with the best yields were EU 1 and 6, with values of 65.92

Fig. 7 Main effects plot for the SN ratio for cumulative methane production.

NmL · g⁻¹ TVS y 62.87 NmL · g⁻¹ TVS, respectively. These units are consistent with the feed concentration of 14 g TVS · L⁻¹ and grinding type I (blender). As mentioned previously, the feed concentration and particle size are key factors for CH₄ production, however, the performance of EU 1 differs with previous studies of the application of food waste pretreatments: Naran *et al.* [43] obtained yields that were around 137.1 mL CH₄ · g⁻¹VSS and 206.4 mL CH₄ · g⁻¹VSS 137.1 mL CH₄ · g⁻¹VSS y 206.4 mL CH₄ · g⁻¹VSS, indicating that the yields obtained in this study were lower than previous studies. On the other hand, the EU with the highest CO₂ yields were units 6 and 11, resulting in 103.63 NmL · g⁻¹ TVS y 57.66 NmL · g⁻¹ TVS, which concur with the feed concentration of 14 g TVS · L⁻¹. Another common factor is the pH, EU 6 presented a pretreatment with a pH of 6.5, and EU 11 did not present any modification, maintaining its acid nature. Based on this, it is possible to attribute the high CO₂ release in the biogas to the poor or null presence of alkaline agents in the system, which could serve as caustic solvents for CO₂ capture in the system.

Fig. 9 shows the main effects analysis for methane yield, in which it is observed that the levels that present a greater effect to increase it are grinding type I (blender), pH 11, temperature 25°C, and an organic load of 14 g TVS consumed · L⁻¹. Grinding, pH, and feed concentration are the most important factors for yield improvement, EU 1 being the one that groups these three factors with their respective levels, differing only in the pretreatment temperature.

Fig. 8 Methane yield per gram of TVS consumed in the EU.

Fig. 10 Percentage of TVS remotion

Fig. 9 Main effects plot for methane yield.

Fig. 10 shows the TVS remotion percentage (removal). The best removals were obtained in EU 5, 10, and 11 with removals of 64.10 %, 63.96 % y 59.28% respectively. On the other hand, the EU with the lowest remotion was EU 1 with a remotion of 40.78%. Based on this, it is considered that the best conditions for organic matter remotion are those implemented in EU 5 (grinding: blender, pH: 6.5, temperature: 60°C, feed concentration: 7 g TVS · L⁻¹).

According to the exposure by Da Silva *et al.* [28], rapidly biodegradable substrates present a degradation kinetic constant (K) value higher than 0.2 d⁻¹. The K value in all EU presents a value above this, both for TVS consumption and methane generation, indicating that food waste is a rapidly biodegradable substrate. When examining the results presented in Table 7, the kinetic values obtained by EU 3 ($K_{\text{degradation}}$ 1.1

d⁻¹, $K_{\text{generation}}$ 0.86 d⁻¹) stand out, since they present the highest TVS degradation rate, as well as the best methane production rate. However, the yields TVS consumed indicate that this unit presented a lower production percentage and methane yield (396.45 NmL CH₄, 47.53% CH₄, 38.54 NmL CH₄ · g⁻¹TVS) than those obtained by EU 1, which, despite presenting lower kinetic values ($K_{\text{degradation}}$ 0.7 d⁻¹, $K_{\text{generation}}$ 0.58 d⁻¹), obtained higher accumulated methane volume, higher methane percentage in the biogas and therefore, better methane yields (646.49 NmL CH₄, 61.83% CH₄, 65.92 NmL CH₄ · g⁻¹TVS). This is explained based on the rate of VFA generation in the system: with a higher rate of TVS consumption, the generation of VFA is higher, when the system presents an accumulation of VFA, they generate a pH decompensation within the system, which leads to the destabilization of the anaerobic process thus reducing the methane production in the process. The acetogenesis and methanogenesis stages are affected by changes in pH which leads to lower methane production [17, 44]. This corroborates that in the case of EU 1, the pretreatment system generated the conditions (pH, alpha ratio, alkalinity, waste availability) to maintain the system able for a long time, improving the methane production process. Additionally, it is considered convenient to evaluate the concentration of NaCl in the food waste, since, as explained by Zhao *et al.* [45], the NaCl present in the food can inhibit the methanogenic processes, decreasing the production of CH₄ in the system.

Table 7 Kinetic constants for degradation of TVS, and methane generation.

EU	$K_{\text{degradation}}$ (d^{-1})	$K_{\text{generation}}$ (d^{-1})	Working Time (d)	Cumulative CH_4	% CH_4	Yields ($\text{NmL CH}_4 \text{ g}^{-1} \text{ TVS}$)
1	0.7	0.58	15	646.49 $\pm$ 94	61.83 $\pm$ 7.09	65.91 $\pm$ 12.50
2	0.4	0.35	23.5	487.44 $\pm$ 16	69.16 $\pm$ 1.01	59.32 $\pm$ 1.91
3	1.1	0.86	9.5	396.45 $\pm$ 17	47.53 $\pm$ 2.34	38.56 $\pm$ 2.79
4	0.8	0.68	12	375.47 $\pm$ 37	62.23 $\pm$ 3.22	43.89 $\pm$ 4.81
5	0.8	0.67	12.5	459.45 $\pm$ 7	60.23 $\pm$ 2.95	40.58 $\pm$ 0.36
6	0.6	0.56	15	470.14 $\pm$ 35	37.75 $\pm$ 2.80	62.86 $\pm$ 2.69
7	0.8	0.67	12	370.58 $\pm$ 48	68.58 $\pm$ 1.33	45.55 $\pm$ 5.45
8	0.8	0.61	13.5	447.78 $\pm$ 34	48.87 $\pm$ 3.12	44.54 $\pm$ 3.06
9	N/A	N/A	0	0 $\pm$ 0	0 $\pm$ 0	0 $\pm$ 0
10	0.8	0.72	11.5	425.60 $\pm$ 14	60.38 $\pm$ 3.12	47.67 $\pm$ 0.22
11	0.7	0.60	14	512.37 $\pm$ 5	45.91 $\pm$ 2.35	48.94 $\pm$ 1.40

4 Conclusions

For this study, the application of pretreatments and the implementation of an inoculum with a high concentration of alkalinity increased the methane production obtained in the anaerobic digestion process of the food waste; by increasing the bioavailability of the substrate with the grinding process, improving the solubility with the thermal treatment and increasing the buffer conditions of the system by means of the chemical agent (Ca(OH)_2), it was able to improve the overall degradation of the substrate, and consequently increase the methane output of the system. In the best conditions (EU 1, grinding type I, pH 11, temperature 60 °C, and feed concentration of 14 g TVS $\cdot$ L⁻¹), a 34.66 % improvement in the yield was achieved, which can be attributed to the general enhancement of the conditions described above; however, being a Bach type test, it is necessary to perform an evaluation in a continuous or semi-continuous regime to determine the viability of the process.

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5 Statements & Declarations

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5.1 Competing Interests

“The authors have no relevant financial or non-financial interests to disclose.”

5.2 Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection

and analysis were performed by Edgar Daniel Alanis Silva, Ma. Del Carmen Chávez Parga and José Apolinar Cortés. The first draft of the manuscript was written by Edgar Daniel Alanis Silva and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Appendix A Graphical Abstract