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ANAEROBIC DIGESTION OF MUNICIPAL BIOWASTE FOR THE PRODUCTION OF RENEWABLE ENERGY: EFFECT OF PARTICLE SIZE

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Abstract – In recent years, Anaerobic Digestion (AD) has become an important technological alternative for the management of municipal biowaste (MBW) for both pollution control and obtaining renewable energy such as methane. One of the factors that most affects the AD of MBW is the particle size, particularly in the hydrolysis and lag phases, this last being in general the limiting stage of solid waste AD. This research evaluated on a laboratory scale the AD of MBW by evaluating Biochemical Methane Potential (BMP) at a temperature of 30 °C during 30 days and the influence of particle size. The particle sizes ranged between < 2 mm to 12.5 mm. Along the study, better results were observed for particle sizes < 2 mm, obtaining productions of methane and electrical energy of 128 mL gVS^{-1} and 2960.4 kWh $week^{-1}$ respectively (19% higher than in reactors with larger particles), thus indicating lower costs for design and maintenance.

Keywords: Anaerobic digestion; Biowaste; Methane; Municipal solid wastes; Renewable energy.

INTRODUCTION

The increasing generation of municipal solid waste (MSW) represents a global problem that has worsened in recent years due to population growth, changes in consumption habits, concentration in urban cores, and the lack of planning. According to a report by the World Bank, in 2012, the generation of MSW reached 1.3 billion tons and it is expected to increase to 2.2 billion tons by 2025 (TWB, 2012).

Municipal biowaste (MBW) comprises the predominant fraction of MSW. These are composed of horticultural waste, pre- and post-consumption food waste from dwellings and commercial establishments, such as restaurants and small grocery stores (Oviedo *et al.*, 2012). In Colombia, MBW constitutes approximately 65% of MSW, and its reuse and exploitation has increased in recent years primarily by activities like composting and recycling (Oviedo *et al.*, 2014). Nevertheless, anaerobic digestion (AD) is an emerging technology that is also promising because the main product generated is biogas, which is an energy-rich product and constitutes an alternative renewable energy source to fossil sources (Hartmann and Ahring, 2005).

Particle size is a factor that can affect the process performance during anaerobic digestion of MBW (AD-MBW). By reducing the particle size the available specific surface area increases and influences the hydrolysis rate in AD and the lag phase, which is the stage of adaptation of microorganisms to the substrate. Moreover, the sizes of the smallest particles can lead to shorter retention times, which entails lower operational costs. Although In the literature there are different recommended particle size ranges (0.1-30 mm), it is recommendable to evaluate this aspect for each particular case (Zhang and Banks, 2013).

Banks *et al.* (2010), in a large scale study, found that with particle sizes between 10 and 30 mm, the optimum

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*To whom correspondence should be addressed methane production was achieved without reaching the point at which particle sizes can cause excessive production of volatile fatty acids (VFAs). In addition, Izumi *et al.* (2010) observed that an excessive reduction in particle size could cause VFAs accumulation, which would decrease the gas production rate and the solubility of the materials subjected to digestion. Lindner *et al*. (2015), evaluated different milling times (0 to 10 min). It was noticed that the pre-treatment process is required in order to achieve an increase in methane production. According to these findings, an optimal range for the particle size still has not been defined nor the variability in sizes obtained during the crushing process of waste, which are parameters that can influence the overall kinetics of the process.

In this study, the effect of particle size on AD-MBW from a municipality that performs separation at the source and selective collection through biochemical methane potential (BMP) tests was evaluated on a bench scale.

MATERIALS AND METHODS

Experimental Location

The tests were performed at an altitude of 970 m above sea level with an average ambient temperature of 23.6°C and a controlled experimental temperature of 35 ± 0.5°C.

Experimental phase

The MBW were provided by a solid waste management plant (SWMP) of a Colombian municipality in which integrated solid waste management is performed, including separation at the source and selective collection. On average, 10.2 t week^{-1} of MBW are generated, of which, 66% has the potential to be digested (Oviedo *et al.*, 2014). The program of MSW sampling and characterization used five samples; these samples were collected following the recommendations of Sakurai (2000).

Prior to physicochemical characterization and BMP testing, all inert material (stones, metal, charcoal, bones) and slowly degrading material (plastic, rubber, and leather) were removed from the MBW samples (Mukherjee *et al.*, 2008). Afterwards, the materials were subjected to grinding as recommended by Sharma *et al.* (1988) using a Waring Commercial CB15 blender at a speed of 15800 rpm for 1 minute (standard equipment speed).

Physicochemical characterization of the MBW was performed according to the ICONTEC (2004) and APHA (2005) guidelines in terms of the following variables: pH (units), moisture (%), total alkalinity (TA) and bicarbonate alkalinity (BA) (mg $CaCO_3$ L^{-1}), volatile fatty acids (mg L^{-1}), acetic acid (%), propionic acid, butyric acid (%), total carbon (%), total and filtered chemical oxygen demand (COD) (mg L^{-1}), biochemical oxygen demand after 5 days (BOD_5) (mg L^{-1}), total nitrogen (%), total ammonia nitrogen (mg L^{-1}), total solids (TS) and volatile solids (VS) (mg L^{-1}). The free ammonia nitrogen was determined in accordance with Sterling *et al.* (2011).

In order to keep the most favorable conditions for anaerobic digestion, an inoculum was used for the BMP tests at a concentration of 1.5 gVS L^{-1}. This came from an anaerobic digester of a municipal wastewater treatment plant (MWWTP) which uses chemically assisted primary treatment and was characterized in terms of the physicochemical variable determined for the substrate. The MBW samples and inoculum were maintained at a temperature not exceeding 4°C for periods of less than seven days prior to setting up the tests.

The analysis of the results of the physicochemical characterization of the MBW and the inoculum were performed through descriptive statistical methods.

Influence of Particle Size on the AD of MSW MBW

The quantification of biogas was performed via the manometric method using an Oxitop® system, which is a pressure-monitoring instrument that consists of a 250 mL reactor with a measurement head that is inserted in the mouth of the reactors and a control that uses an infrared interface for data transfer. The tests were performed in a WTW TS 606-G/2-I incubator with intermittent manual agitation for 720 hours (Aquino *et al.*, 2007). The working volume was 200 mL, which left a free space of 50 mL to store the biogas produced based on the recommendations of Aquino *et al.* (2007).

Considering that the techniques used to determine methane production are standardized methods aimed at guaranteeing the most favorable conditions to bolster the AD of the substrate, a solution of macro- and micronutrients was used (Owen *et al.*, 1987), and the pH was adjusted to 7.0 with a 4% $NaHCO_3$ solution to maintain stable conditions in the BMP tests. Each experimental unit had its respective duplicate (n=2) and a control (inoculum with distilled water) for the determination of endogenous methane production. To ensure that the manometric biogas measurement corresponded predominantly to methane, carbon dioxide was captured by means of NaOH pellets (Pabon *et al.,* 2012), and the residual gas composition was verified via gas chromatography (GC2014 chromatograph).

The volume of methane at standard conditions (SC) was determined in accordance with Giménez *et al.* (2012) in which the proportion of dissolved methane was considered. The experiments were conducted at an S/I ratio of 0.25 $gVS_{substrate}\, gVS_{inoculum}^{-1}$ (Raposo *et al.*, 2006).

The steps were performed during the pretreatment stage, where 1 kg of an MBW sample was taken at different grinding times (60s-T1, 120s-T2, and 180s-T3) at a speed of 15,800 rpm (standard speed of the instrument) to obtain different particle sizes as suggested by the literature (<30 mm) (Aldin *et al.*, 2011).

Approximately 500 g were extracted from the sample to determine the particle size. This portion of sample was dehydrated in an oven at a temperature between 55-60°C for 48 h or until a constant humidity was reached. The particle size of the dehydrated samples was determined using the sieve analysis technique for fine and coarse aggregates (ASTM C136-01) (Bojórquez *et al*., 2011). Sieves of sizes of ½, No. 4, No. 8, No. 10, No. 16, and No. 60 were used. The predominant particle size was determined in each reactor via granulometry curves, and the D_{60} and D_{10} values were likewise considered; with these the uniformity coefficient was found (Cu) by applying Eq. 1. A value of Cu < 3 indicates that the particle size distribution is uniform, whereas values of Cu > 3 indicate that the particle size in the sample is heterogeneous.

$$\mathrm{Cu} = \frac{\mathrm{D}_{60}}{\mathrm{D}_{10}} \tag{2}$$

In Eq. 1, Cu is the uniformity coefficient, D_{60} is the particle size that is less than or equal to 60% of the MBW weight, and D_{10} is the particle size that is greater than or equal to 10% of the MBW weight.

Each of the crushed samples was subjected to AD, maintaining the aforementioned conditions of the substrate/inoculum (S/I) ratio and pH. Figure 1 shows the scheme for this phase of AD of MBW.

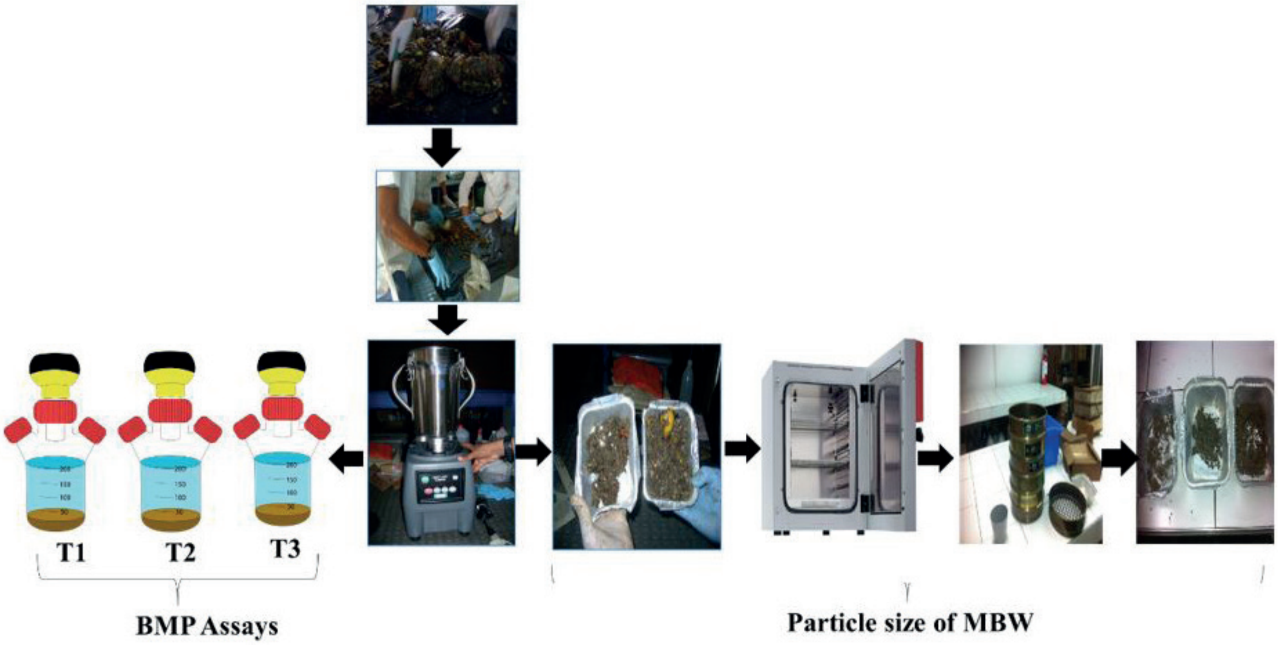

Figure 1. Schematic of the setup.

To determine the effect of the evaluated factor, a randomized, non-parametric permutation test with p<0.1 was conducted, in which the response variable was the BMP. The statistical analysis was performed by employing the R i386 3.0.2 statistics package.

To analyze hydrolysis as a limiting stage, a first-order kinetics model (Liew *et al*., 2012) and the well-known Gompertz model were applied. In the first-order kinetics model, Eqs. 2 and 3 were applied to obtain the concentration (mol L^{-1}) from the pressure and the hydrolysis constant, respectively.

$$M(t) = \frac{P(t)}{R * T} \tag{1}$$

where M(t) is the methane concentration at time t (mol L^{-1}), P(t) is the pressure registered by the OxiTop® instrument (atm) at time t, R is the ideal gas constant (atm L mol^{-1} K^{-1}), and T is the experiment temperature (K).

$$ln\left(\frac{M_U}{M}\right) = K_h t \tag{3}$$

where *ln* is the natural logarithm; t is the time (d), Mu is the methane production at the end of the experiment (mol L^{-1}), M is the remaining gas production over time (M=Mu-M(t)) and K_h is the hydrolysis constant (d^{-1}).

The modified Gompertz model can identify significant parameters related to the hydrolysis stage of anaerobic digestion, such as the maximum production rate, maximum production and lag phase, which emphasize the time when the substrate transforms and its relation to the stage of methane production. The model corresponds to a sigmoidal function expressing methane production in the reactor as a function of time (Eq. 4) (Lay *et al*., 1997):

$$V_{CH4}(t) = P_{max}\exp\left[-exp\left(\frac{R_{max}\exp(1)}{P_{max}}(\lambda - t) + 1\right)\right] \tag{4}$$

where $V_{CH4(t)}$ is the cumulative methane production (mL h^{-1}), P_{max} is the maximum cumulative production at the end of the experiment (mL), R_{max} is the maximum rate of methane production (mL h^{-1}), is the lag phase (d); and t is the methane generation time (h).The correlation coefficient (R^2) was used as criterion to assess the fitted models through the software Polymath 5.0 and Microsoft Excel 2007.

Furthermore, to theoretically understand the potential for electrical energy generation via methane produced during AD of MBW, Eq. 5 was used by considering the fraction of MBW at the locality (Schievano *et al.*, 2014).

$$EE = \text{BMP x } 8.7917\text{x } 0.39 \text{ x GMSW x FMB} \qquad (5)$$

where EE is the electrical energy generated (kWh $week^{-1}$), BMP is the biochemical methane potential of the MBW (m^3 kg^{-1}), 8.7917 is the conversion factor of methane to kWh (kWh $m^{-3}CH_4^{-1}$), 0.39 is the factor of electrical energy production based on internal combustion, GMSW is the generation of MSW in the locality (t $week^{-1}$), and FMB is the fraction of MBW present in MSW (66%).

Finally, the reduction of greenhouse gas (GHG) was quantified and a net energy balance was carried out for each of the ranges of particles obtained. To determine GHG reduction equations suggested by IPCC (2006) and Liu *et al*. (2012) were used (See Table 1) and two scenarios were considered. In the first, the disposal of MBW in landfills is emphasized, taking into account that the theoretical methane production was 240m^3 t^{-1}, in agreement with previous studies in the MBW of the town (Parra *et al.*, 2014). On the other hand, the second scenario relates to the use of MBW by DA, considering direct methane emissions into the atmosphere equivalent to 10% of total production in the form of dissolved methane.

Table 1. Equations for determining GHG

Scenario	Equation	Parameter
Landfill	$G_1 = BMP * DCO_f/MW_{CH4} * F * V_{SC}$ (6)	**BMP:** Biochemical Methane Potential (m^3 t^{-1}) **BMP_d:** Biochemical Methane Potential dissolved (m^3 t^{-1}) **DCO_f:** Fraction of the degradable organic carbon (0.5) **MW_{CH4}:** Molecular weight methane (16 g mol^{-1}) **F:** Value of global warming potential of methane (21) **V_{SC}:** Volumen standard conditions (22.4 L) **MW_{CO2}:** Molecular weight carbon dioxide (44 g mol^{-1}) **0.39:** Is the factor of electrical energy production based on internal combustion **C:** Heat value of methane (35.9 MJ m^{-3}) **F_E:** GHG emission factor of power generation with capacity more than 1000 MW (0.8578 kg-CO_2kWh^{-1})
	$G_2 = BMP * DCO_f/V_{sc} * MW_{CO2}$ (7)	
	$G_3 = BMP * DCO_f * 0.39 * C/\frac{3600}{1000} * F_E$ (8)	
Anaerobic Digestion	$G_4 = BMP_d * DCO_f/MW_{CH4} * F * V_{SC}$ (9)	
	$\boldsymbol{G_{Tlandfill}} = G_1 + G_2 - G_3$ (10)	
	$\boldsymbol{G_{TAD}} = G_4 + G_2 - G_3$ (11)	

G_1 and **G_4**: Quantify direct emissions to the atmosphere; **G_2**: emission from power generation; **G_3**: GHG offsetting by power generation; **$G_{Tlandfill}$**: Carbon footprint for landfill and **G_{TAD}**: Carbon footprint for anaerobic digestion

For net energy balance (E_{net}) in each of the treatments Serrano *et al.* (2015) recommended the use of equations 12 to 14.

$$E_{\ in} = P_d * t/C_s * V_d \qquad (12)$$

where E_{in} is the energy entering the process (J gVS^{-1}), P_d is the power consumption of the grinding machine (1800 J s^{-1}), t is the time of grinding (s), C_s is the concentration of substrate in each experimental unit (gVS L^{-1}) and V_u is the effective volume of the reactor (L).

$$E_{\ out} = BMP * C * F_r \qquad (13)$$

where E_{out} is the energy that is generated during the process (J gVS^{-1}); C heat value of methane and F_r is the percentage recovery of methane (90%).

$$E_{net} = E_{in} - E_{out} \qquad (14)$$

RESULTS AND DISCUSSION

Characterization

The results of physicochemical characterization of MBW and inoculum are presented in Table 2.

Table 2. Physicochemical characterization of MBW and inoculum

Parameter	MBW*^{n}	Inoculum*^{n}
pH	5.5±0.1	7.2±0.2
Moisture (%)	76.7±3.2	94.1±0.4
TA (mg L^{-1} $CaCO_3$)	4447.1±1248.8	6270.4±1389.5
BA (mg L^{-1} $CaCO_3$)	-	3390.3±772.9
VFA (mg L^{-1})	10595.5±1086.4	1656.6±59.9
Acetic acid (%)	<0.0001	<0.0001
Propionic acid (%)	<0.0001	<0.0001
Butyric acid (%)	<0.0001	<0.0001
Total solids (mg L^{-1})	113036.67±15240.7	74090±29574.6
Volatile solids (mg L^{-1})	93016.7±28527.5	28258.9±10592.6
TOC** (%)	37.9±2.3	10.2±0.5
COD_{total} (mg L^{-1})	137839.1±72267.1	54852.6±23184.5
$COD_{filtered}$(mg L^{-1})	35604.5±3600.1	4,048.5±600.6
BOD_5 (mg L^{-1})	45333.3±1800.3	1273.9±150.4
Total nitrogen**(%)	1.7±1.0	0.5±0.01
Total ammonia nitrogen (mg L^{-1})	324.5±55.2	393.2±44.5
Non-ionized ammonia nitrogen (NH_3)(mg L^{-1})	0.13±0.1	7.9±0.1
Ionized ammonia nitrogen (NH_4^+) (mg L^{-1})	324.3±48.2	385.3±38.2

*Average values ** Dry basis; n: number of samples (5)

In general, the values of pH, moisture, TA, BA, and VFAs are typical of quickly acidificable wastes, as evidenced by other authors such as Pesta (2007) and Zupančič and Roš (2012), who studied AD of MBW. The low pH values are linked to the MBW decomposition associated with high moisture; this causes an increase in VFA production and the absence of BA. Therefore, it is evident that MBW must be conditioned with an alkalizer that can provide the necessary buffer capacity to neutralize the acidity and not affect the AD of the MBW (Abdulkarim and Abdullahi, 2010). The results of chromatography of the VFAs show that the high levels of VFAs are not linked to short-chain acids (acetic, propionic, and butyric acids) that are the precursors of the phases linked to methane production. As a result, the absence of these can prolong hydrolysis times and microbial adaptation due to the possible presence of long-chain or branched fatty acids (Sundberg *et al.*, 2011).

The high content of humidity in the MBW favors the hydrolysis stage, which is the initial stage of the AD process. The organic matter content in the MBW is high, as evidenced by the values of TOC, COD, BOD_5, and VS (see Table 2). In addition, the $COD_{filtered}/COD_{total}$ ratio (0.26) indicates that the predominance of particulate material can also influence the hydrolysis of organic matter, which increases the solid retention time (SRT) (Mata *et al.*, 2000).

The pH influences the predominant form of nitrogen, which is an important factor in biological processes due to the likely occurrence of phenomena inhibitory to microbial activity (Dinamarca *et al.*, 2003). Ammonia nitrogen in the form of ammonium ions predominated in the MBW at a concentration of 324.3 mg L^{-1}, and the content of non-ionized ammonia nitrogen, which is the more toxic form, was 0.13 mg L^{-1}. From the point of view of the contribution to the buffer capacity, authors such as Parawira *et al.* (2004), recommend a concentration on the order of 1100 mg L^{-1} for adequate AD of this type of waste; these data confirm the necessity of using an alkalizer in the process.

The MBW had a C/N ratio between 20 and 30, which has positive effects on AD (Raposo *et al.*, 2006). This value can be related to the high content of total nitrogen, which is associated with the presence of proteins in MBW.

The inoculum had values typical of anaerobic sludge from municipal wastewater treatment plants (MWWTP) which uses chemically assisted primary treatment with values of pH, TA, and BA that are indicative of a good buffer capacity that favors AD (see Table 2) . Despite the fact that the value of the VS/TS ratio is low from the point of view of the degree of activity of the biomass present in the sludge, it is typical of anaerobic reactors at MWWTP which uses chemically assisted primary treatment. Nevertheless, it is important to understand that the VS/TS ratio alone is not a good indicator of the inoculum quality, owing to the microbial diversity present in the sludge.

Influence of Particle Size on AD of MBW

The results of the granulometry tests on MBW according to grinding time are shown in Table 3.

According to Table 3, for all of the grinding times, a particle size suitable for AD of MBW was obtained (0.1-30 mm) (Aldin *et al.*, 2011). Cho *et al.* (2013) remarked that the predominance of particles of less than 2 mm facilitates metabolic processes in AD, and when the proportion of these particles decreases, methane generation is affected. Therefore, for a grinding time of 60 s (T1), 68.4% of the particles had diameters of less than 2.0 mm, whereas for T2 (120 s) and for T3 (180 s), the values were 52 and 53.6%, respectively. Consequently, the predominance of this type of particle in T1 facilitates such important phases as hydrolysis and therefore affects the production

Table 3. Granulometry of MBW

Sieve	φ (mm)	Retained Weight (g)			% Retention			% Accumulated Retention			% Passing		
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
½”	12.5	4.92	0.00	0.00	1.30	0.00	0.00	1.30	0.00	0.00	98.70	100	100
No 4	4.75	58.29	46.28	75.94	15.30	12.00	18.90	16.60	12.00	18.90	83.40	88.00	81.10
No 8	2.36	24.01	79.93	109.15	6.30	20.70	27.20	23.00	32.60	46.00	77.00	67.40	54.00
No 10	2.00	32.69	59.39	1.40	8.60	15.30	0.30	31.60	48.00	46.40	68.40	52.00	53.60
No 16	1.18	129.46	83.56	81.87	34.10	21.60	20.40	65.60	69.60	66.80	34.40	30.40	33.20
No 60	0.25	104.29	87.04	114.14	27.40	22.50	28.40	93.10	92.00	95.20	6.90	8.00	4.80
Background	0.00	26.33	30.80	19.49	6.90	8.00	4.80	100	100	100	0.00	0.00	0.00
TOTAL (g)		**380**	**387**	**402**									

φ :diameter.

of methane (Hajji and Rhachi, 2013). In spite of using the same grinding time, only 6.9% of the particles obtained a diameter of less than 0.25 mm, which indicates a lack of fine particles. Although accelerating the MBW transformation process can also increase the VFA concentration during the hydrolytic stage of AD; this can lead to inhibition of the microorganisms (Izumi *et al*, 2010).

Although it is expected that, with a longer grinding time, the particle size should decrease, it was found that for times T2 and T3, particles larger than 2.0 mm predominated (48 and 46.4%, respectively) compared to that obtained with T1 (31.6%).

This result can be associated with the agglomeration process of smaller particles due to the effect of van der Waals forces, which is attributed to nonpolar substances, such as VFAs, in particular those with long-chains; it can be deduced that there were large concentrations in the substrate utilized in this process (Pasquali *et al.*, 2006). Therefore, with greater exposure times of these particles to the centrifugal effect of the grinding process, the grouping of smaller particles is perhaps favored.

Figure 2 shows the granulometry distribution curves for each MBW sample. This figure indicates that 60% of the particles (D_{60}) for T1, T2, and T3 are smaller than 2.0, 2.2 and 2.8 mm, respectively, whereas the effective diameter (D_{10}) consists of particles with sizes less than 0.25, 0.33 and 0.388 mm, respectively. Upon finding 10% of the particles with this diameter, it was observed that there was no prevalence of these particles, which thereby avoids rapid acidification and possible inhibition; according to Izumi *et al*. (2010), an excessive reduction in size can increase the VFA concentration in the reactor.

Acording to Diaz and Giraldo (1997), the smaller particle size means a greater amount of inoculum required in the reactor and, consequently, the amount of substrate to be treated decreases. Nevertheless, for all of the samples, the uniformity coefficient, Cu, was greater than 3 (Table 4), which indicates the variability of particle sizes. This result agrees with the investigations performed by Zhang and Banks (2013), who assert that during the grinding processes, different particle sizes are achieved; these can influence certain phases of the AD process, particularly hydrolysis, when the greatest enzymatic activity during the anaerobic process occurs.

Figure 3 shows that the lag phase for the latter was approximately 2.5 d (60 hours), which indicates that although the substrate predominantly contains particulate organic material, its size not only allowed adaptability of the biomass but also the microbial communities rapidly transformed the MBW (Mata *et al*., 2000). This result is reflected on day 19 (456 hours) of the digestion process when the reactor had already reached approximately 80% of the methane production, thereby demonstrating the importance of particle size in AD of MBW. Likewise, during the entire process, it can be observed that reactor T1 achieved the greatest methane production, which is attributed to the high content of particles smaller than 2.0 mm.

Table 5 shows the results of the kinetic model and Gompertz adjusting for each particle size.

The K_h results show the predominance of particles that facilitate the transformation process and the generation of methane (Aldin *et al*., 2011). Also, it was found that the greater correlation was achieved for particles with sizes smaller than 2 mm (T1) (0.17 d^{-1} and 0.92, respectively), which is linked to the results of particle size where such particles predominated.

In addition the lag phase was less than 1 day, which coincides with the size of particles that facilitate the hydrolysis stage, since the overall speed of the process is primarily associated with high solids substrates. Even where acidogenic and methanogenic stages are considered limiting, the hydrolysis may affect the overall process. Similarly, the particle size possibly facilitated substrate assimilation by microorganisms, owing to the prevalence of MBW long chain acids that are characterized by reducing methane production time.

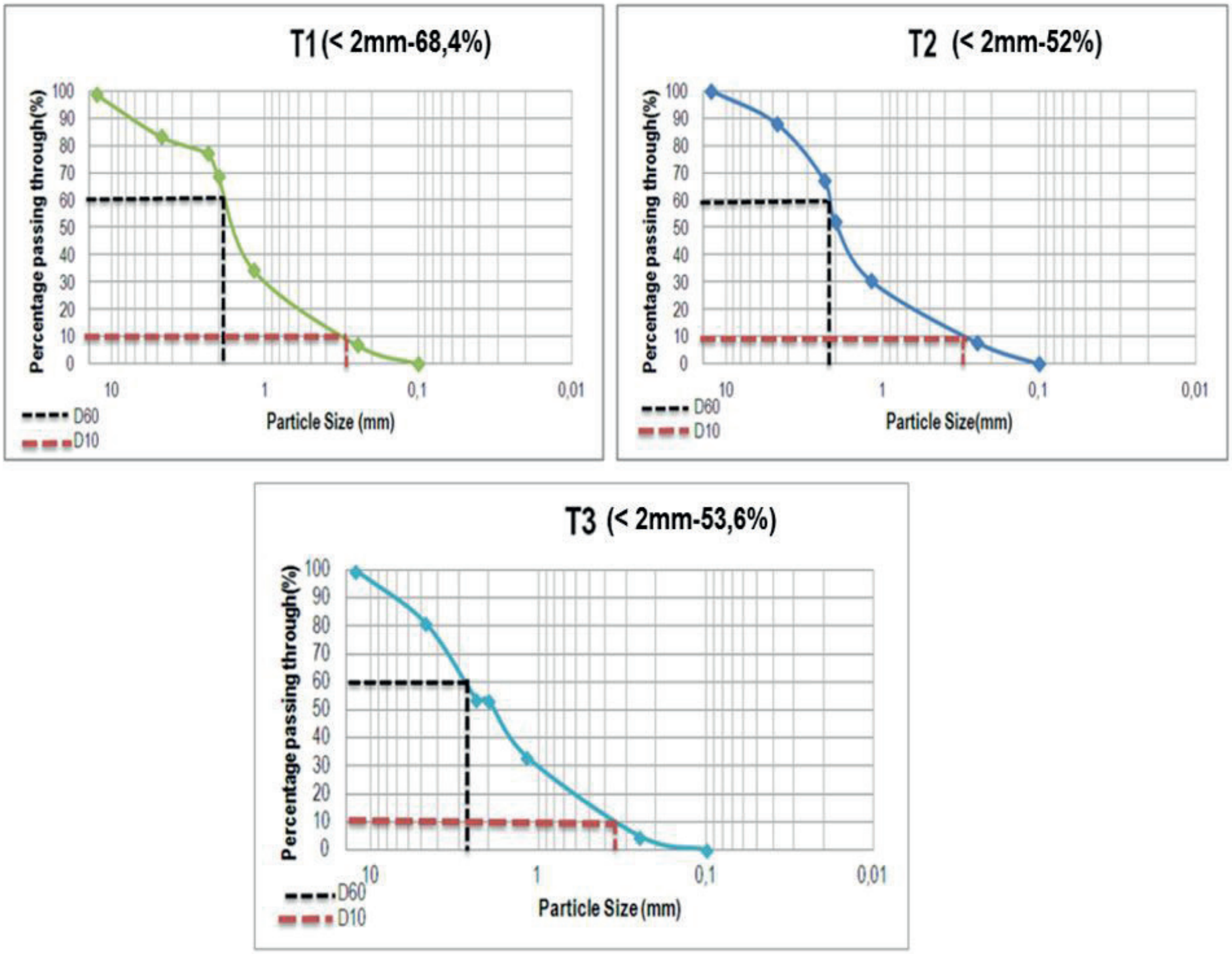

Figure 2. Granulometry for each of the samples.

Table 4. Uniformity coefficients for each of the samples

Parameter	T1	T2	T3
Cu	6.0	7.3	8.0

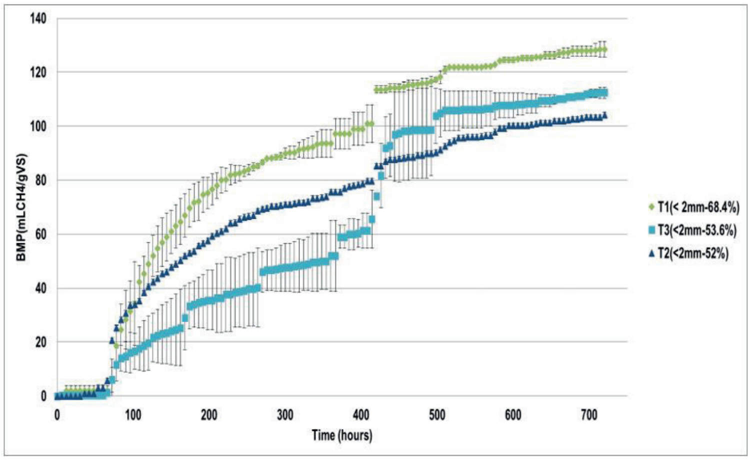

Figure 3. Biochemical methane potential for each particle size.

Table 5. Results of first-order kinetic model and modified Gompertz for each particle size

Factor	Level	first-order kinetic model		Modified Gompertz equation				
		K_h (d^{-1})	R_1^2	λ^a	$R_{max}^{\ b}$	$P_{max}^{\ c}$	PBM^d	R_2^2
Particle size (mm)	T1 (<2mm-68.4%)	0.17±0.05	0.92	1.0±0.05	0.029±0.01	9.36±0.22	128±1.4	0.98
	T2 (<2mm-52%)	0.12±0.02	0,89	0.30±0.02	0.015±0.01	7.04±0.11	104±9.0	0.98
	T3 (<2mm-53.6%)	0.13±0.04	0.89	0.32±0.02	0.027±0.01	8.77±0.52	112±2.1	0.98

a (days); b (mL h^{-1}); c (mL); d (mL gSV^{-1})

Although variability among the values in the lag phase for each time was observed, this may be related to the results of Cu, since heterogeneity was found in particle size; hence the diversity of sizes may have influenced these results. This is consistent with studies by Aldin *et al*. (2011), who observed that by increasing the hydrolysis rate there is a decrease in the particle size.

The results of BMP and EE production are presented in Table 6 for each of the evaluated particle sizes.

Table 6. BMP and EE for each reactor evaluated

R	BMP ($mLCH_4\ gVS^{-1}$)	EE (kWh $week^{-1}$)
T1 (<2 mm-68.4%)	128±1.4	2960.38±73.44
T2 (< 2mm-52%)	104±9.0	2405.24±532.10
T3 (<2mm-53.6%)	112±2.1	2595.68.±47.33

R-Reactor

The non-parametric randomization test evaluates the significance of particle size in AD and showed there are no differences in BMP at a 10% significance level. However, upon observing the values of BMP and EE, the best results were observed in reactor T1, given that a production exceeding 19% was achieved compared to other times. This finding is similar to that reported by Cho *et al.* (2013), who found an increase in the production of methane of 20% in reactors with particles with diameters of less than 2.0 mm, which is the predominant size in T1. Agyeman and Tao (2014) obtained the best results with regard to methane production in reactors in which particles of < 2.5 mm predominated. Therefore, the importance of particle size on processes in AD of MBW reflected in the methane production is confirmed.

According to the Unified Information System (SUI, for it is initials in Spanish) (SUI, 2013), the municipality under study had an energy demand of 1206839 and 653097 kWh for the residential and non-residential (commercial, industrial, and public) sectors, respectively. If the electrical energy production obtained from T1 is considered, approximately 12% of the residential demand and 22% of the non-residential demand could be supplied. By considering that the average annual kWh cost for the residential sector in the Valle del Cauca province is COP$381.3 (USD $0.16), a savings of COP$54076271(USD $22688.98) could be achieved, which indicates that AD not only has positive environmental impacts but also economic impacts.

An energy rationing scheme similar to that implemented in the 1990s in Colombia can be applied again considering that 70% of electricity consumed originated from hydroelectric sources, and the Mining Energy Planning Unit (MEPU, Unidad de Planeación Minero Energética-UPME) (UPME, 2013) has expressed that prolonged dry periods (caused by the El Niño phenomenon) have directly impacted the water reservoir contribution to hydroelectric generation. Due to the aforementioned factors, the use of MBW as a potential energy alternative for the country could permit fulfilling current legal regulations related to renewable energy (Law 1715 of 2014) and promote the energy independence of the country.

Figure 4 shows that actually the AD of MBW is an alternative that reduces greenhouse gas emissions, since a reduction of over 90% was obtained. Landfills in Colombia represent 5% of the country´s emissions compared to developed countries such as Macedonia and South Africa where the percentages are 4.3 and 7%, respectively. (Friedrich and Trois, 2013; Dedinec *et al.*, 2015). The GHG generated by the disposal of solid waste in these structures are not considered as a serious problem when viewed from the local point of view, but high concentrations may be generated by a lot of these structures, both controlled and uncontrolled and spread throughout a region, a country or continent. The continuity in time of their emissions into the atmosphere and the persistence of these gases can generate an endless string of changes in the composition of natural systems, which transform the weather conditions as evidenced by the prolongation of the El Niño phenomenon in recent years.

Figure 5 shows the results of the energy balance for each particle size range evaluated.

From the perspective of energy balance it shows that, for all treatments, this is negative (see Figure 5); however, T1 is the closest to an energy balance (-985408 J gVS^{-1}) than the E_{net} for T2 and T3 of -2510644 and -3964850 J gVS^{-1}, reflecting that the grinding time in the pretreatment of the MBW associated with the particle size is a factor that should not only influence the biological process of the AD of the MBW, but also the energy demand for this technology. Therefore, when extrapolating the results at pilot or full-scale one must consider the grinding time obtained in the trials of BMP. A grinding time that ensures optimum particle size that maximizes methane production and minimize E_{in} is not yet established, that is to say, environmentally sustainable. This is similar to Ariunbaatar *et al.* (2014), who state that mechanical pretreatment, although enhancing methane production from the energy and environmental balance, is the least favorable compared to other pretreatments such as thermal and biological.

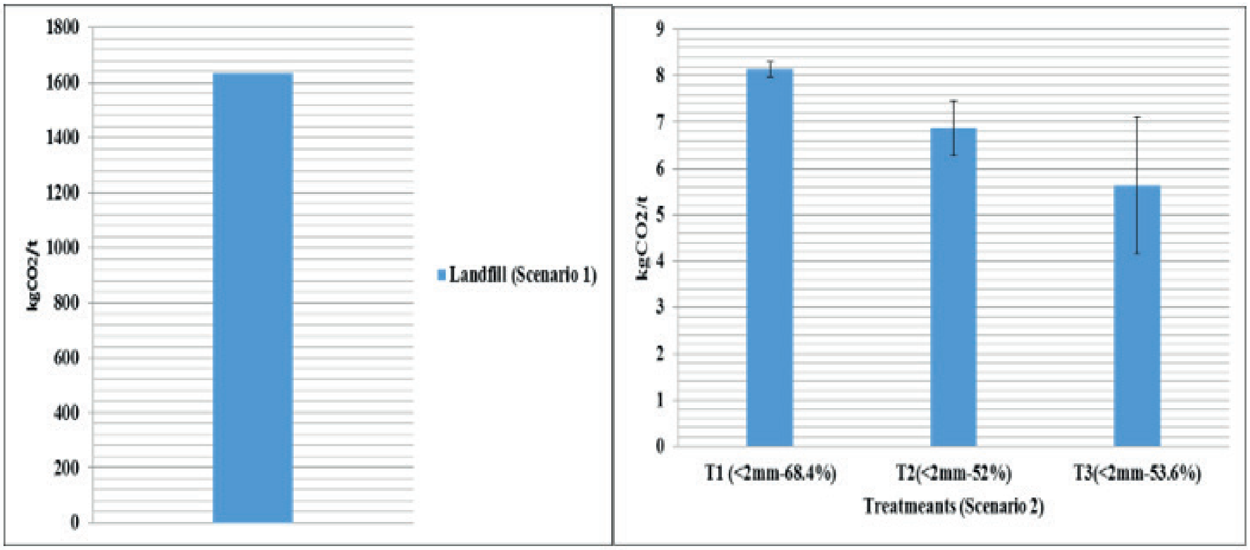

Figure 4. Carbon footprint for each of the proposed scenarios

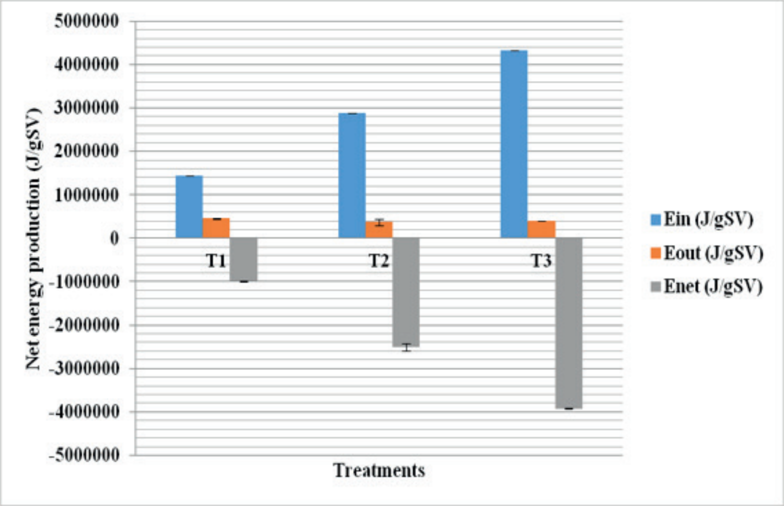

Figure 5. Energy balance for each particle size range evaluated

CONCLUSIONS

The MBW studied had a composition of primarily particulate organic material. In addition, the biodegradable fraction is significant; this confirms its potential as an alternative source of renewable energy based on anaerobic digestion.

The present study highlights the importance of the separation process at the source and the selective collection of solid waste in communities because to the success of this type of alternative technology depends on these factors.

The particle size is an important factor in the AD of MBW, presenting better results for the hydrolysis rate, the lag phase, methane production and electricity generation in the size range of particle below 2 mm. Likewise, it evidences that AD is a technological alternative that reduces the emissions of greenhouse gases in developing countries, which are more susceptible to climate change. AD considers the combination of mechanical pretreatments to ensure a positive energy balance and in turn maximize the production of methane and thus power generation.

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