

Comparison of biogas production obtained from samples of Mitú and Sibundoy municipal solid waste

Comparación del potencial de producción de biogás obtenido a partir de residuos sólidos urbanos provenientes de Mitú y de Sibundoy

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ABSTRACT

This study compares the calorific power of biogas obtained from the municipal solid waste (MSW) of two towns in Colombia, whose populations are affected by deficiencies in the supply of electricity. The production of biogas would represent an important opportunity to meet these needs, taking advantage of the solid waste generated, in whose composition organic material predominates (45 %). For this purpose, MSW samples were taken from the municipalities of Mitú (Vaupés) and Sibundoy (Putumayo), in order to establish their relevance to produce biogas. For each sample, the organic waste was characterized in terms of its macroscopic composition, moisture content, ash, volatile and total solids. Subsequently, the composition of biogas obtained was determined from anaerobic digestion tests with biological sludge as inoculum in different proportions and the calorific value of the gas was calculated. It was found that organic waste from both municipalities is suitable to produce biogas due to the physicochemical characteristics of the samples, the high methane content generated and, therefore, the satisfactory calorific power for its use in the production of electrical energy.

Keywords: Biogas, Anaerobic digestion, Municipal solid waste, Energy potential.

RESUMEN

En este trabajo, se realiza una comparación del poder calorífico del biogás obtenido a partir de residuos sólidos urbanos de dos municipios de Colombia, cuyas poblaciones son afectadas por deficiencias en el suministro de energía eléctrica. La producción de biogás representaría una oportunidad importante para suplir tales necesidades, aprovechando los residuos sólidos que se generan, en cuya composición predomina el material orgánico (45 %). Por esto, se tomaron muestras de RSU de los municipios de Mitú (Vaupés) y Sibundoy (Putumayo), con el fin de establecer su pertinencia para la producción de biogás. En cada muestra se caracterizaron los residuos orgánicos en términos de su composición macroscópica, contenido de humedad, cenizas, sólidos volátiles y totales. Posteriormente, se determinó la composición del biogás obtenido a partir de ensayos de digestión anaerobia con volados biológicos como inóculo en diferentes proporciones y se calculó el poder calorífico del gas. Se encontró que los residuos orgánicos de ambos municipios son adecuados para la producción de biogás por las características fisicoquímicas de las muestras, el alto contenido de metano generado y, por tanto, un poder calorífico satisfactorio para su aprovechamiento en la producción de energía eléctrica.

Palabras clave: Biogás, Digestión anaerobia, Residuos sólidos urbanos, Potencial energético.

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Introduction

Some studies have concluded that municipal solid waste constitutes a very important source in the generation of energy. The production of biogas is one of the simplest options that can be implemented globally at different scales (Sosnowski, Wiczorek, and Ledakowicz, 2003). Some of the main advantages are the reduction of waste generated by people sending it to a unit of final disposition and the energy use and its adaptability to more or less expensive technologies, according to the particular needs of each user (Tock and Schummer, 2017; Morgan et al., 2018).

Biogas comprises a mixture of gases including methane, carbon dioxide, low amounts of hydrogen, nitrogen, hydrogen sulfide and traces of other gases. Biogas is produced by the decomposition of organic matter under anaerobic conditions, in conjunction with the generation of energy and new biomass

due to the action of various microorganisms (FNR, 2010), (Moya, Aldás, López, and Kaporaju, 2017). The main interest for its production lies in its use as a source of heat, electricity and fuel for vehicles, since its calorific value could be close to that of natural gas (MINENERGIA/PNUD/FAO/GEF, 2011).

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Municipal solid waste management is a major challenge for cities, as their characteristics should define the strategies to be adopted in each case. According to some studies, the lack of education in terms of waste management is greater in developing countries, resulting in serious pollution problems, facilitating the deterioration of ecosystems and increasing diseases among the population. It has also been shown that by providing training on the benefits of waste management and recycling, the risk of acquiring the aforementioned problems is significantly reduced, in addition to improve people's perception of paying fees related to the costs of basic sanitation (Han et al., 2018).

In Colombia, various initiatives have been developed to promote renewable energy generation. These initiatives include the implementation of cogeneration systems in specific industries, the strengthening of research in different technologies and the establishment of Law 1715 of 2014. This law promotes the development and use of unconventional sources of energy in the national energy system, through its integration into the electricity market, its participation in non-interconnected areas, other applications for a sustainable economic development, the reduction of greenhouse gas emissions from fossil fuels, and the national security of energy supply (Congreso de Colombia, 2014). Thus, it is worth evaluating the potential for energy production by using unconventional sources in municipalities with low coverage in the country, mainly in non-interconnected areas.

Mitú is the capital of the department of Vaupés, which is located in the Colombian Amazon. It has a population of 31 568 inhabitants including indigenous and settlers. They occupy almost 16 500 km², where 98 % are covered by tropical forest (Alcaldía de Mitú, 2016). The population is concentrated in the urban area and has an index of unsatisfied needs equivalent to 51,8 %, which include health problems related to unhealthy hygiene practices, low coverage of the aqueduct and sewerage services, in addition to the presence of an open cast dump for the disposal of residues (~8 t/day), from which 45 % corresponds to the organic fraction. A diagnosis for the 2016-2019 action plan indicated that there is a low level of civic awareness in the classification and final disposal of waste that generates risks for the population and the environment, such as unauthorized burning and direct disposal to waterways (Alcaldía de Mitú, 2016; Villamil, 2016).

Mitú is part of the 70 municipalities that are not yet within the interconnected electricity system of the country and that exceed in more than 200 % the national average of electricity consumption, besides having no natural gas supply ("U.N. promueve. . .", 2018). Some of the reasons for this situation include the heterogeneity of their territories, the lack of management by service providers and cultural aspects of the users (Superservicios, 2018b).

In contrast, Sibundoy is within the interconnected energy system, but pays one of the most expensive electricity rates in the country (Superservicios, 2018a). The municipality of Sibundoy is located in the department of Putumayo and has approximately 14 396 inhabitants, including some indigenous

reservations (22 %). Most of the people are concentrated on the urban area. In the municipality, there are paramo ecosystems and wetlands of national importance. In terms of coverage of public services, Sibundoy has 76,2 % of coverage of sewerage service and 91,5 % of electricity (DNP, 2019). This municipality has a waste separation system at the source within its territorial management model, where organic and inorganic solid waste is collected separately. Comprehensive solid waste management uses organic waste for composting and other recycling activities of nonbiodegradable materials. Unmet basic needs ratio is 20,7 % (Alcaldía de Sibundoy, 2011).

According to the foregoing, this study evaluates the potential production of biogas from the solid urban waste of the municipalities of Mitú and Sibundoy through anaerobic digestion, in order to establish if it would be suitable for the implementation of a municipal production system of biogas, which allows to formulate some strategies for the stabilization of the process, according to the environmental conditions of these municipalities.

Materials and methods

Samples of organic matter were obtained from solid waste collection centers in the municipalities of Mitú and Sibundoy. In the first municipality, samples were collected from the municipal battalion and the center for the collection of solid urban waste, while in Sibundoy samples were taken directly from the collection center of solid organic waste, whose separation is carried out directly by the community. Standardized sewage sludge from the food industry was used as inoculum.

For the samples of Mitú, a classification of the solid residues was made, conserving the organic fraction, while the inorganic components were separated for their final disposition. For the samples coming from Sibundoy, such classification was not necessary, since there is separation at the source in this municipality. The samples of interest were then subjected to a reduction stage by liquefying with a proportion of $m_W: m_{OFMSW} = 1,16 \text{ g}_W/\text{g}_{OFMSW}$ to facilitate its homogenization.

Subsequently, homogeneous samples were characterized to determine pH, moisture percentages (% M_{WB}), ash (% A_{DB}), volatile solids (% VS_{DB}) and total solids (% TS_{DB}), following the biomass characterization standards established by the National Renewable Energy Laboratory (NREL) of the United States of America. Specifically, NREL/TP-510-42621:2008 and NREL/TP-510-42622:2008 standards were used to determine the percentage of moisture and ash, respectively. According to the values obtained, the percentages of volatile and total solids were estimated (NREL, 2019). The pH of the initial sample was also determined.

For the analysis of biomethane potential (BMP), the BMP-RBP equipment of Anaero Technology was used with 1 L reactors, under constant agitation and times of hydraulic retention (THR) between 5 and 18 days. The process temperature was adjusted to 28 °C, in order to normalize it to the average ambient temperature of Mitú. For the estimation

of the production potential of biogas, the samples were subjected to digestion with and without addition of inoculum, adjusting the initial pH conditions to values between 6,7 and 7,3. The relations of volatile substrate solids to volatile inoculum solids were established in $0,5 \text{ gVS}_{OFMSW}/\text{gVS}_{SS}$, $0,25 \text{ gVS}_{OFMSW}/\text{gVS}_{SS}$ and $0,17 \text{ gVS}_{OFMSW}/\text{gVS}_{SS}$. In addition, tests for anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) were carried out without the addition of inoculum in order to evaluate the possibility of establishing a system of chimneys in sanitary landfill, since it is an economic option and would involve minor structural changes in the collection system for the capture of biogas (López, 2016; Lavagnolo, 2019).

The compositions of methane, carbon dioxide, oxygen and hydrogen sulfide were determined using the 5 000®BIOGAS equipment. The samples were collected in hermetic bags in maximum periods of one to three test days for reading.

The calorific value for each sample was weighted on the basis of the gas percentages established. The higher heating value (HHV) and lower heating value (LHV) were obtained from the literature and compared with the calorific value data generated in the combustion enthalpy formulation, according to the respective chemical reactions for each substance that comprises the biogas.

Figure 1 describes the process methodology for assessing the biogas potential of samples.

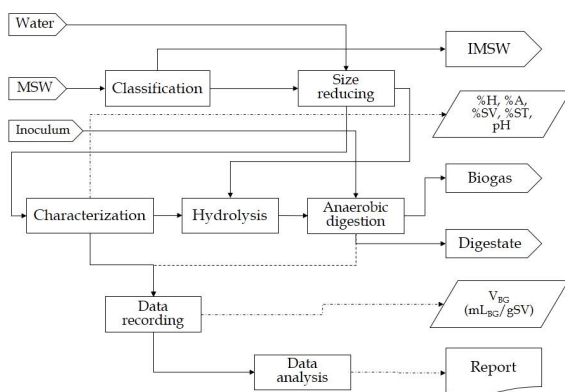


Figure 1. General process scheme for the assessment of biogas potential.

Source: Authors

Results

In samples from Mitú-Vaupés, inorganic contaminants were found, such as plastics, metals, synthetic fibers, among others, which make it difficult to carry out the tests. The organic fraction contained traces of food, such as cassava, fruits, eggshells, bananas, peas, carrots, leaves, and some meat residues. Components such as cob shells, pea pods and branches had difficult degradation during the process, also making it difficult to reduce the samples sizes.

In the case of residues from Sibundoy – Putumayo, a high content of plant residues was found, which is suitable for use as substrate in anaerobic digestion for biogas production. The

low content of inorganic contaminants that inhibit production was also remarkable. Plant residues present a large quantity of fibrous material (lignocellulosic), whose degradation is less efficient than in other substrates. This condition can be improved with pretreatments such as reducing residue size and using thermal treatments or longer hydrolysis times. Table 1 describes the results of a general characterization of the selected samples of Mitú and Sibundoy.

Table 1. General characterization of the selected samples for anaerobic digestion tests (average values)

Sample	Vegetable waste (%)	Meat waste (%)	Plastics (%)	Others (%)
Mitú	94,7	4,2	1,1	0,0
Sibundoy	97,4	0,7	1,0	0,9

Source: Authors

Regarding the characterization of the homogeneous material obtained from pretreatment, Table 2 shows that Mitú samples have a moisture content between 73,97% and 82,52%, exceeding other values reported in the literature, where the organic fraction of a sample of OFMSW is about 70% (Moya et al., 2017). This may be related to the humidity conditions in the municipality and the exposure of waste to the atmosphere. It is also noted that the volatile solids content of solid waste is 83,1% on average, which is an acceptable interval with respect to other studies reported in the literature, where the percentage of volatile solids for OFMSW is between 70% and 95%, corresponding to the organic matter consumed by the microorganisms during the anaerobic digestion. The pH values reported for OFMSW are between 5,2 and 6,3 (Zupančič and Grilc, 2012). Low pH values could be explained by the relative high degradation of ODSs, considering both their age and contamination with possible inorganic residues.

For the municipality of Sibundoy, the characterization allowed to find a high content of minerals and inorganic material (according to the percentage of ash) that compete with the fraction of volatile solids. These values are within the same orders of magnitude reported in the literature and they represent a raw material suitable for anaerobic digestion in terms of their nutritional value. Additionally, a higher pH is observed than in the samples of Mitú and values that are within the range reported in other sources.

Table 2. Specific characterization of Mitú and Sibundoy samples

Sample	Moisture	Ash	Volatile solids	Total solids	pH
	M_{wb} (%)	A_{db} (%)	VS_{wb} (%)	TS_{wb} (%)	
Mitú	77,94 ± 3,98	16,70 ± 3,58	83,30 ± 3,58	22,06 ± 3,98	4,75 ± 0,51
Sibundoy	75,08 ± 3,36	29,39 ± 0,34	70,61 ± 0,34	24,92 ± 2,28	5,56 ± 0,41

Source: Authors

After subjecting the samples to digestion with and without inoculum, the composition of biogas was determined in order to compare the amount of methane in the samples and estimate its value for energy use. Tables 3 and 4 show the results of the gas composition obtained from different organic load ratios for Mitú and Sibundoy, respectively.

Table 3. Composition of biogas from Mitú samples collected. Average from 21 days of biogas production

Organic load	CH ₄ (%)	CO ₂ (%)	O ₂ (%)	H ₂ S (%)	Others (%)
Digestion without inoculum	0,8	55,7	2,9	>>>	33,9
S/I = 1:2	58,7	34,9	0,9	0,06	5,5
S/I = 1:4	65,5	30,5	0,5	0,14	3,5
S/I = 1:6	58,7	34,4	1,0	0,10	5,9

Source: Authors

Samples from Sibundoy showed that the methane content is higher when the ratio of substrate to inoculum is 1:2 (volatile solids basis), while for samples from Mitú the best concentration of methane was obtained from the 1:4 substrate to inoculum ratio. Furthermore, it is estimated that digestion without addition of inoculum is not appropriate for this type of residue, as a result of the content of methane found for the samples of Mitú and Sibundoy.

Regarding the quantity of methane compared between the ratio 1:2 and 1:4 in the samples of the two municipalities, the percentages of methane obtained are good and, taking into account that the samples are raw, the quality of the OFMSW is favorable in terms of the amount of microorganisms and contaminants that could inhibit the activity of the inoculum, in this case of sludge.

Table 4. Composition of biogas from Sibundoy samples

Organic Load	CH ₄ (%)	CO ₂ (%)	O ₂ (%)	H ₂ S (%)	Others (%)
Digestion without inoculum	0,1	77,5	1,4	0,98	20,4
S/I = 1:2	67,0	25,7	2,5	0,05	4,8
S/I = 1:4	58,6	35,0	1,8	0,08	4,6

Source: Authors

Tables 5 and 6 show the results of the calculation of the HHV and LHV for the biogas obtained from the samples of Mitú and Sibundoy, respectively. The obtained values are within the range of heating values reported in the literature, i.e. for biogas the LHV is between 17 and 34 MJ/m³ depending on the percentage of methane present in the mixture (Flotats, 2016), while values of HHV are reported between 15,5 and 26 MJ/m³. This shows again that the quality of biogas obtained from solid waste of Mitú is comparable to others of similar origin (IDAE, 2014).

Table 5. Higher and lower heating values of biogas obtained from Mitú samples

Organic load	HHV (MJ/m ³)	LHV (MJ/m ³)
Digestion without inoculum	0,5	0,5
S/I = 1:2	21,4	19,3
S/I = 1:4	23,8	21,5
S/I = 1:6	21,4	19,2

Source: Authors

Thus, the testing of the samples of Mitú, whose volatile solids ratio was 1:4, presented the greatest HHV, while in Sibundoy samples the best relation obtained was 1:2. This is

because the estimated heating values depend directly on the concentration of methane.

Table 6. Higher and lower heating values of biogas obtained from Sibundoy samples

Organic load	HHV (MJ/m ³)	LHV (MJ/m ³)
Digestion without inoculum	4,6	4,2
S/I = 1:2	25,4	22,9
S/I = 1:4	22,3	20,1

Source: Authors

Discussion

Samples from Mitú and Sibundoy showed a similar gross composition, after removing the larger contaminants from the samples of Mitú. Differences in the pH are observed, which is related to the age of the residues of each municipality and, in the case of samples of Mitú, the influence of its predominant climate. Mitú has an average temperature of 28 °C, while Sibundoy has 16 °C. It is also noted that plant residues constitute the major part of the samples. This may be related to the diet of the population in this region. The results of physicochemical characterization, in particular the content of volatile solids, showed that the samples possess suitable properties for their use in anaerobic digestion.

The amount of methane per unit volume of biogas obtained was higher for Sibundoy samples at S/I = 1:2, whereas for Mitú samples at S/I = 1:4. Biogas was generated with a higher amount of methane. This may be related to the inoculum tolerance to the presence of contaminants and the nature of the substrate. A possible explanation of the behavior of the obtained data is that as the presence of inorganic contaminants increases in the biogas production system, the tolerance of microorganisms to high substrate loads is negatively affected and thus methane production decreases. For the ratio S/I = 1:4, the samples of Mitú generated a higher percentage of biomethane, as well as a higher amount of H₂S, which is a sign that the interactions between populations of microorganisms in the reactor had greater difficulties in the chain of reactions that allow the generation of methane in the biogas.

In addition, a test was carried out to determine the production of methane from the residues, without the addition of inoculum. These tests considered the adoption of biogas recovery by chimneys, such as those implemented in some existing sanitary landfills, given their low cost and production (Lavagnolo, 2019). However, the percentage of biomethane in the mixture was found to be minimal, in contrast to a high production of H₂S, hence this option was discarded.

Finally, it was determined that the biogas obtained in the samples is suitable for applications in electric energy production, after comparing its calorific powers with reports of the literature. From an analysis of the amount of residues generated each day, in Mitú approximately 9 431 m³ BG/month could be generated, corresponding to about 77,9

kWh/h and in Sibundoy is about 5 050 BG/month and 41,7 kWh/h.

Conclusions

The analysis of samples from Mitú and Sibundoy allowed to deduce their aptitude to produce biogas through anaerobic digestion. The differences presented in their characteristics are related to the particular conditions of each municipality and the influence of each sample was observed on the percentage of methane obtained per unit of volume of biogas. Additionally, an analysis of the potential of biomethane in each municipality showed that some of the difficulties of each municipality could be overcome through the management of solid waste, the reduction of costs in energy fees and the possible supply of natural gas if required. To conclude, this type of management must be implemented, considering the advantages for non-interconnected areas and low-cost energy production.

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Nomenclature

A: ash.

BMP: biomethane potential.

DB : dry basis.

HHV : higher heating value.

HRT: hydraulic retention time.

LHV : lower heating value.

M: moisture.

MSW : municipal solid waste.

OFMSW: organic fraction of municipal solid waste.

SS : sewage sludge.

TS: total solids.

VS: volatile solids.

W : water.

WB : wet basis.

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