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Design of an anaerobic biodigester model as an alternative for methane generation
Diseño de un modelo de biodigestor anaerobio como alternativa para la generación de metano

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Abstract

The application of anaerobic biodigesters in municipal wastewater sludge is important for the generation of methane being an alternative for the generation of renewable energy, the research is peculiar because it is carried out at 3812 masl, in the area surrounding Titicaca lake at a temperature variation between -1.3 to 16.8 °C. The objectives were: i) Design an anaerobic biodigester for methane generation and ii) Evaluate the amount of methane contained in the biogas generated by the sewage sludge of the three wastewater stabilization ponds. The methodology consisted of constructing a prototype design of an anaerobic biodigester with adequate performance for methane generation from sewage sludge, for which the biodigesters were loaded with 11 kg of sewage sludge collected from three stabilization ponds. The results indicate that the anaerobic biodigester works adequately for methane generation, produced in the biodigesters, reached up to 36.7 % in 33 days of retention time at thermophilic temperature between 50 to 60 °C, the factors that influenced the low methane generation are the low C/N ratio and the low concentration of organic matter, which varied between 21.0 to 51.10 %.

Resumen

La aplicación de biodigestores anaeróbicos en lodos de aguas residuales municipales es importante para la generación de metano siendo una alternativa para la generación de energía renovable, la investigación es peculiar debido a que se realiza a 3812 msnm, en el área circundante al lago Titicaca a una variación de temperatura entre -1.3 a 16.8 °C. Los objetivos fueron: a) Diseñar un biodigestor de digestión anaerobia para la generación de metano, b) Evaluar la cantidad de metano producido en el biogás generado por lodos residuales de tres lagunas de estabilización de aguas residuales municipales. La metodología consistió en construir un diseño prototipo de un biodigestor anaeróbico con un funcionamiento adecuado para la generación de metano a través de lodos residuales, para lo cual se cargó los biodigestores con 11 kg de lodos residuales recolectados de tres lagunas de estabilización. Los resultados indican que el biodigestor anaeróbico funciona adecuadamente para la generación de metano, producido en los biodigestores, alcanzaron hasta 36.7 % en 33 días de tiempo de retención a temperatura termofílica entre 50 a 60 °C, los factores que influyeron en la baja generación de metano son la baja relación C/N y la baja concentración de materia orgánica, la que varió entre 21.0 a 51.10 %.

Palabras clave:

Biodigestor anaerobio,
diseño,
lodos residuales,
materia orgánica,
metano.

Introduction

In the coming years the supply of fossil fuels will be scarce and costly[1], so the search for sustainable energy alternatives, such as biofuel (BF) generation, is necessary[2]. The use of BF is a growing demand for transport[3], allows for the replacement of petroleum-based diesel fuel[4]. The sustainability of first-generation BF such as ethanol and biodiesel have been strongly criticized as such BF would jeopardize food security[5]. As a result, biogas generation has increased and various safe and efficient treatment processes have been developed[6-8]. The production of biogas from sewage sludge (SS) is important[9], brewery sludge[10], livestock manure[7,11], which through a process of anaerobic digestion (AD) produce methane, which can be transformed into clean energy as a solution to the problem of water pollution and greenhouse gas (GHG) emissions[12]. Such AD can occur through single-stage anaerobic biodigesters, where all stages of AD (hydrolysis, cytogenesis, acidogenesis and methanogenesis) are carried out in one environment, but require strict pH control[12]. In addition to methane, carbon dioxide, nitrogen, hydrogen, hydrogen sulphide and oxygen are produced in the biogas[6].

In order to analyse whether biogas from sludge AD is a viable alternative for energy generation, it is necessary to determine the amount of methane produced, as several studies have indicated that the minimum concentration of methane it should contain should be between 55 to 78 % and that, to reach this optimum concentration, the temperature required should be between 30 to 60 °C and its C/N ratio 25 to 35 °C[6,11,13].

Stabilisation lagoons (SL) are widely used technologies for wastewater (WW) treatment in Latin America, mainly because of their low cost of construction and operation. However, most of the time they represent an environmental and social problem, due to the accumulation of sludge, which can be used in biogas generation, being this an alternative energy source that has no geographical or technological limitations[14]. For example, in Mexico, around 640000 t of SS is generated annually, which can be used in energy production[9].

Research on obtaining methane from the pre-treatment of silage and alkaline grass in biodigesters recorded 0.6 and 11.2 % methane in the biogas produced, while with raw grass silage in the biodigester and alkaline pH recorded 6.5 to 11.3 % methane[10], Also in the process of fresh leachates and domestic WW, for 90 days, the results reported a production of biogas[15]. The AD system with biodigesters includes hydrolysis, acidogenesis, acetogenesis and methanogenesis processes. Therefore, the digestion process depends on the interaction of temperature, pH, nutrients, operating conditions and the type of biodigester[16].

On the other hand, AD is a biochemical process that consists of the degradation of organic matter (OM) from WW[17], Likewise, the co-digestion of WW sludge is a strategy to optimize the digestion of the SS, under mesophilic conditions (35 °C) using batch biodigesters, to obtain the maximum methane production[18]. The control and use of methane require estimating, with reasonable certainty, the daily and cumulative production[19], being important to control the pH around 7, average temperature of 40 ºC[20], through the use of laboratory-scale experimental biodigesters, which uses sludge from AR treatment lagoons[21]. Municipal solid waste presents a high environmental problem, however, it can be obtained and used for methane generation[22], through an AD process, the biodegraded material generates gases such as carbon dioxide and methane. The intensity and duration of the anaerobic process varies depending on several factors: temperature, pH of the biodegraded substrate, on average 17.33 L/d of biogas and 53 % methane can be obtained[23], avoiding the accumulation of solid waste and GHG emissions such as methane (CH_4), carbon dioxide (CO_2)[24], biogas can also be obtained using a domestic anaerobic biodigester from household generation of organic waste in urban and rural areas[25,26], mainly containing waste such as offal, blood and faeces which are rich in essential substrates that produce biofuel generating up to 87 % methane in 28 days of incubation[27].

The Puno region is located at 3812 m above sea level, the month with the highest temperature is November (16.8 °C), the lowest temperature is recorded in July (-1.3 °C), a constraint for the application of temperature-dependent technologies for methane generation. WWs are treated through SL, which have accumulated high volumes of sewage sludge, currently an unused resource. This accumulation has caused the retention time of WW to be shorter, resulting in little or no treatment. On the other hand, unpleasant odours are frequently generated, affecting the health of the surrounding population. Therefore, an alternative solution to these problems is the generation of methane from these WW with the use of biodigesters adapted to these climate conditions.

The objectives of this research were: i) To design an anaerobic biodigester for methane generation and ii) To evaluate the amount of methane contained in the biogas generated by LR from the three wastewater stabilisation lagoons.

Materials and methods

The biodigesters were installed in the Ecology Laboratory of the Faculty of Biological Sciences of the National University of the Altiplano.

Design of the biodigesters. Three biodigesters were designed, wooden incubator type whose base area is 50 x 50 cm^2, with a height of 60 cm, whose interior space is thermally insulated with polystyrene covered with plywood. A biodigester tank consisting of a cylindrical polyethylene drum with a capacity of 16 L in the space of 2/3 of the drum is used for the biodegradation of sludge under anaerobic conditions[17], the remaining volume was used to store the biogas, a manual agitator, stopcocks, a pH sensor, a homogenization system, for which a galvanized wire butterfly agitator with an aluminum support was built, and finally the hermetically sealed biodigester tank to generate a strictly anaerobic system[9,12]. It was then placed in the incubator type box, heated and illuminated by two 25 watt bulbs each, at thermophilic temperature in the range of 50 to 60 °C controlled by a TC-1000 thermistor, relative humidity of the installed environment varied between 44 to 60 %. Each biodigester was fitted with a gas hose to facilitate the recording of methane concentration during AD. Three trials of 33 days’ retention time each were carried out (Figure 1).

Collection and characterization of SS from the SL located in the cities of Puno, Juliaca and Ilave, mud samples were obtained. The Espinar SL in Puno has 23 ha, the Challacollo SL in Ilave has 21 ha and the Chilla SL in Juliaca has 30 ha. Sampling and AD processes in the biodigesters were carried out in February (first sampling), May (second sampling) and July (third sampling) 2018 (Table 1).

Figure 1 Schematic of the biodigester designed for the anaerobic digestion process of SS

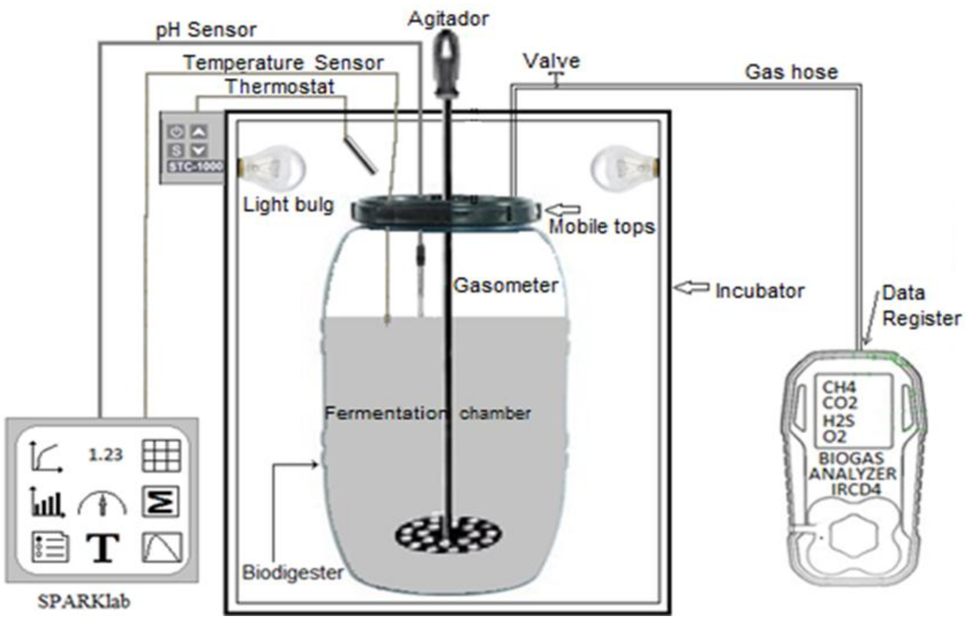


Table 1 Geographical location of LR sampling points in the wastewater stabilization ponds in the cities of Puno, Juliaca and Ilave

City		UTM coordinates		Distance (m)	Altitude (masl)	Observations
		North	East			
Puno	1	8 246 702	392 673	434	3812.00	On the shores of Titicaca lake
	2	8 246 953	392 592		3812.00	
	3	8 246 916	392 786		3812.00	
	4	8 247 038	392 637		3811.50	
Ilave	1	8 222 796	433 096	800	3832.00	On the banks of the Ilave River
	2	8 222 846	433 016		3832.50	
	3	8 222 852	433 112		3832.00	
	4	8 222 800	433 190		3 831.50	
Juliaca	1	8 286 432	382 010	600	3834.00	Near the Coata River
	2	8 286 370	382 096		3834.00	
	3	8 286 327	382 034		3834.00	
	4	8 286 392	381 990		3834.00	

The collection of SS samples was carried out between 06:00-08:00 h in the three stabilization ponds simultaneously, using personal safety implements. In each lagoon, there were four sampling points: i) at the inlet, ii) at the outlet and iii) two lateral sampling points. Samples were collected with a shovel at a distance of 1 m from the edge of the bank and at a depth of 0.30 to 1.20 m. 3 L of SS was collected at each sampling point, resulting in 12 L of composite sample, 11 L were used to load the biodigesters and 1 L was sent to the laboratory for WW physicochemical analysis. In the composite sample from each lagoon, a temperature in the range of 7 to 11 °C (higher in February and lower in July) and pH between 6.5 and 7.0 (basic to near neutral) were recorded in situ using SparkLab equipment.

Biogas measurement. To maintain AD conditions, temperature (measuring range -35 to 135 °C, resolution 0.01 °C), pH (measuring range 0 to 14 pH, resolution 0.001) were monitored with SparkLab digital equipment. The generated biogas was measured with a Biogas Analyzer IRCD4 series M18814014, which measures CH_4 (measuring range 0 to 100 %, accuracy ±3 %) and CO_2 (measuring range 0 to 100 %, accuracy ±3 %). To homogenize the composite mixture in the fermentation chamber, a manual stirring operation was performed 30 min before recording the data. The microbial load could not be recorded, since our main objective was to determine the methane concentrations.

Statistical analysis. To compare the percentage of methane generated from the SS of the three stabilisation ponds, the non-parametric Kruskal Wallis test was applied, as the data did not meet the assumptions of normality and homogeneity of variances. In addition, a regression test was applied to determine the relationship between methane percentage and time (days). Analyses were performed in the INFOSTAT software version 2018, licensed for use E001-280.

Results

Characteristics of the LRs. Phosphorus concentration ranged from 0.24 to 1.68 %, potassium from 0.15 to 3.48 %, OM from 21.00 to 51.10 %, carbon from 12.17 to 29.60 %, nitrogen from 1.44 to 6.77 % and C/N ratio reached up to 12.67 (Table 2).

Table 2 Phosphorus, potassium, organic matter, carbon, nitrogen and C/N ratio of SS from the three stabilisation ponds in the Puno region. First experiment (February to March), second experiment (May to June) and third experiment (July to August 2018)

Experiment	Lagoon	Phosphorus %	Potassium %	Organic matter (%)	Carbon (%)	Nitrógen (%)	C/N
First	Puno	1.68	3.48	22.60	13.09	6.23	2.10
	Juliaca	1.50	3.55	21.00	12.17	6.08	2.00
	Ilave	1.41	3.38	23.16	13.42	6.77	1.98
Second	Puno	0.88	0.14	37.90	21.96	2.39	9.20
	Juliaca	0.87	0.17	39.40	22.85	2.47	9.25
	Ilave	0.48	0.15	30.20	17.52	1.44	12.17
Third	Puno	>1	0.38	51.10	29.60	3.04	9.74
	Juliaca	0.61	0.40	43.90	25.50	2.22	11.49
	Ilave	0.24	0.31	35.20	20.40	1.61	12.67

Methane generation. From the LR from the Juliaca stabilisation pond, 29.21 % methane was obtained on average, from the Ilave stabilisation pond 11.45 % and from the Puno stabilisation pond 25.78 % (Figure 2).

No significant differences in methane generation were found between the LRs of the three stabilisation ponds (H =3084.34, P =0.0001). The behavior of methane generation in the three SS had different regression coefficients in relation to the log data in relation to time (days). For example, for Puno, r^2= 0.71, a= 30.41, b= -0.28, for a total of 1395 methane generation data records (%), for Juliaca r2= 0.62, a= 27.79, b= 0.38, for a total of 1479 data and finally for Ilave r2= 0.06, a= 13.08, b= -0.10 for a total of 1411 data (Figure 3 and Table 3).

Discussion

Biodigester design. The three biodigesters are the result of three tests, the two previous designs, had failures with the control of temperature, pH and methane. The third biodigester design works adequately in conditions of 3812 meters above sea level, however, to increase the percentage of methane in the biogas, it is important to control the pH, the temperature that should not exceed 60 °C, carry out a co-digestion process with other materials such as: manure from pigs, cattle and South American camelids. The economic cost of the construction of each biodigester was around 180 US $.

Figure 2 Percentage of methane generated from SS from the stabilisation ponds of Puno, Juliaca and Ilave, through an anaerobic digestion process in thermophilic biodigesters n= 4285

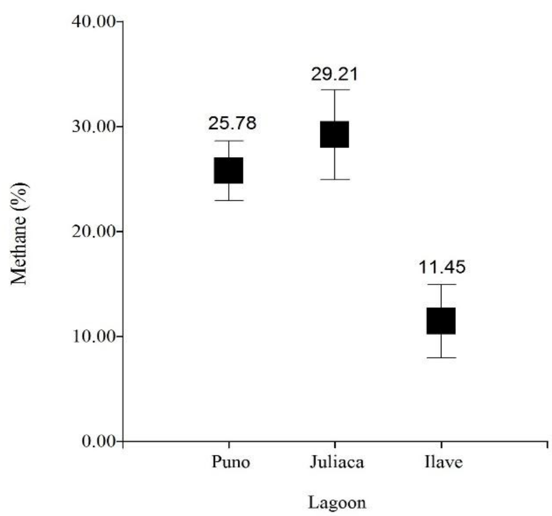


Table 3 Regression analysis (Y=a+bx) of methane (%) in relation to retention time of 33 days in thermophilic biodigester system for SS of the stabilisation ponds of Puno, Juliaca and Ilave 2018

Lagoons	a	b	r^2	<P	Data
Puno	30.41	-0.28	0.71	0.0001	1395
Juliaca	27.79	0.38	0.62	0.0001	1479
Ilave	13.08	-0.10	0.06	0.0001	1411

The designs that were adapted are based on the existing information of full-phase anaerobic biodigesters (hydrolysis, acetogenesis and methanogenesis) and others that can be modified according to the volume of biomass treatment[12].

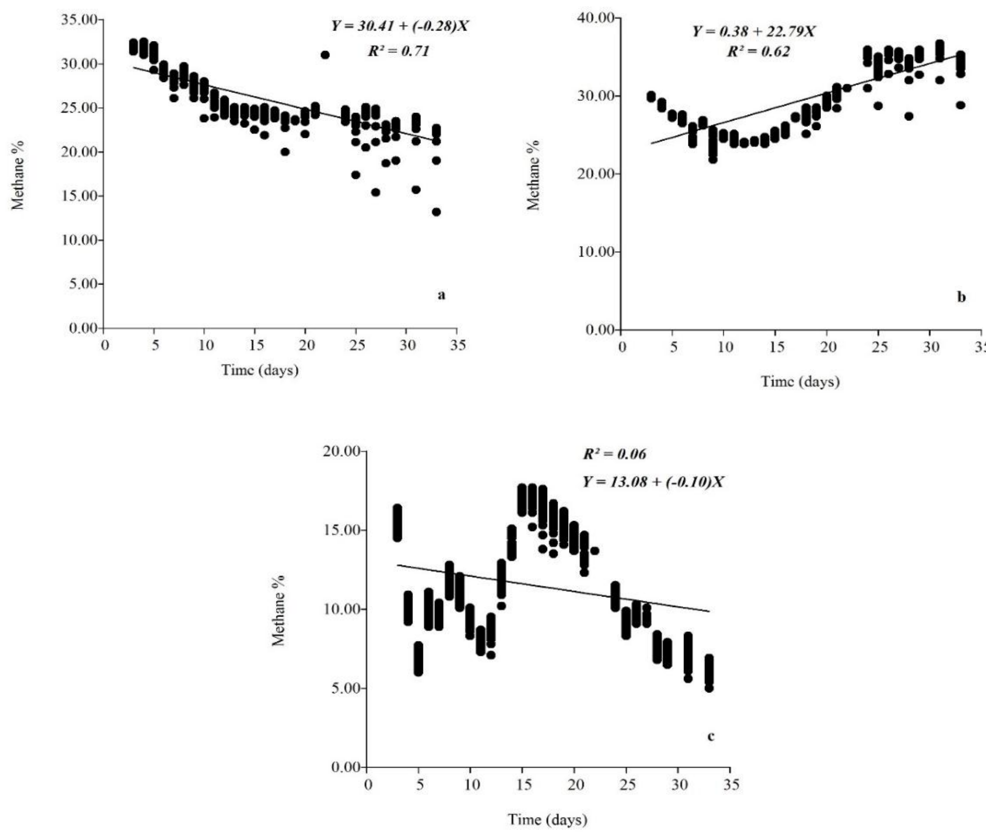
Characterization of SS. The OM composition of the WW SLs, the main input for methane generation, fluctuates for Puno from 22.60 to 51.10 %, Juliaca from 21.0 to 43.90 % and Ilave from 23.16 to 35.20 %. The WW treatment plants are the raw material for methane generation in the LE of Puno, Juliaca and Ilave. This form of energy would allow in the future to reduce the use of fossil fuels[1], it is important that SS accumulated in SL can be transformed into methane, therefore, these infrastructures are a main source for safe and efficient renewable energy (RE) generation[6-8]. Methane, which can be obtained from SL, can be used as an energy source[9,14], for the availability of SS in SL and/or WW treatment plants in the Puno region, using a low-cost technology such as the AD.

However, the SS found in the ponds under study were below the recommended C/N parameters and did not reach the C/N ratio parameters, which are between 25 and 35[6], furthermore, for higher methane production, it could be supplemented with cattle waste and algae after an anaerobic co-digestion process[28].

Methane generation from SS. The low methane generation recorded up to a maximum of 29 % does not allow to obtain a good methane quality for energy production, which should be in the range of 55 to 75 %[7], however, through a co-digestion process, the percentage of methane generation can be increased[8].

Regarding the LE of Juliaca, it has a higher percentage of generation, by presenting a greater amount of OM, than the lagoons of Puno and Ilave, this difference is probably influenced by the greater number of inhabitants that generate WW, also, the influence of time (days), is important, for example, for the SL of Puno between the first 5 days 32.09 % of methane was obtained and decreased until day 33 to 22.6 %, having a minimum variation of 13.2 to 32.5 % of methane. For Juliaca between the first 5 days it starts with 29.9 % of methane registering an increase until day 33 with 36.7 %, having a minimum variation of 21.8 % and a maximum of 36.7 % of methane.

Figure 3 Methane variation (%) in relation to 33 days of monitoring in thermophilic SS biodigesters of stabilisation ponds in Puno (a), Juliaca (b) and Ilave (c)



Finally, Ilave between the first 5 days starts with 14.5 % methane, registering a decrease until day 33 with 6.9 % methane, having a minimum variation of 5.0 to 17.7 % methane. These variations are related to the amount of OM, which each LE possesses. However, other authors register up to 85 % methane in the first 15 to 18 days, with a pH range of 5.5 to 8.5 and a temperature of 30-60 °C and C/N ratio between 25 and 35 °C[6], these records are well below the percentages found in the research in the SL of Puno, Juliaca and Ilave, there are several possibilities to increase the percentage of methane, such as: co-digestion of cattle manure, sludge from the brewery, increase of ammonia[6,7,13], between 15 and 30 days, cattle manure generates a higher percentage of methane[11], up to 76.5 % methane is achieved with grasses, with forages we can generate more methane[29].

The construction of the biodigesters for this research was adequate in design and operation, the limitation in methane generation was the amount of OM in the SS. As recommended by other authors, the biodigesters were controlled at a temperature of 50 °C, at 60 °C and at 60 °C[30]. However, other studies also obtained low records of 0.6 to 11.2 % methane from the pre-treatment of grass silage[10], also with domestic WWs in 90 days, biogas production was negligible[15]. Comparatively in our research, we were able to obtain up to 37 % methane, due to the increase of OM, considered as a co-digestion process. The innovative aspect of the research is the design and construction of a biodigester for the production of methane, which can later be converted into RE. In the biodigester, it is important to control the processes of hydrolysis, acidogenesis, acetogenesis and methanogenesis and these are related to temperature, pH, nutrients, operating conditions, etc[31].

The results of this research can be applied to reduce total GHG emissions in the future[31], because in biodigesters pollutants are removed or converted into viable energy alternatives. This removal is through anaerobic and aerobic systems with temperature and pH control[32]. It is the main reason that drives many developing countries to seek waste-to-energy technologies, which at the same time eliminate the accumulation of large amounts of waste, therefore, many countries seek modern technologies to convert waste generated into energy[33], agricultural residues also have enormous potential in the form of energy and nutrient recovery[34]. Finally, the utilisation of SS from treatment plants, SL, solid waste, have the possibility to generate energy as alternative fuels, e.g. methane[35].

In most cities, there is inadequate sludge management, which eventually enters rivers, lakes and lagoons, degrading their ecosystems. So a viable alternative is to treat such sludge through the AD process[17], obtaining methane as clean energy. In the study the pH control had limitations, it was only controlled at the beginning and at the end of the process, however, it is essential to monitor the pH permanently through anaerobic induction mechanisms[20].

The use of organic waste and obtaining biofuel, is a viable alternative to reduce the accumulation of solid waste and GHG emissions such as methane CH_4, carbon dioxide CO_2 and CO_2[24].

The AD, used for organic waste from restaurants, also generates biogas through a 200 L anaerobic biodigester for 240 days, with pH between 4.8 and 6.3 and the biogas yield was 0.22 m^3/kg[36], Comparisons with the research carried out were smaller in terms of biodigester size and retention time, this situation is likely to have affected a lower methane generation. However, it is also important to increase methane generation by testing the pig manure AD process, considering the C/N ratio, since this ratio is fundamental for microbial development and for the stabilisation of organic matter[37], further research can be done on the AD process with poultry manure, onion waste, which can increase the C/N ratio[38].

It was expected to obtain between 50 to 80 % methane in the designed biodigesters, one of the important limitations was the low OM content of the three SL, an alternative is to continue with research through an AD process to increase the percentage of methane to convert it into useful energy.

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Conflicts of interest

The authors declare that they have no conflict of interest.

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Ethical considerations

The research complied with the ethical standards of the information process.

Research limitations

There were no limitations to the research.

Authors' contributions

Ángel Canales-Gutiérrez, participated in the idea, project design, drafting of the manuscript and statistical data processing. *Blanca Jacqueline Quispe-Aucca,* participated in the installation, data collection, drafting of the manuscript and final revision. *Ricardo Romero-Loaiza,* in installation, data collection and drafting of the manuscript. *Nazario Villafuerte-Prudencio,* in design, drafting of the manuscript and final revision. *Janette Rosario Ramos-Pineda,* participated in drafting of the manuscript and final revision. *José Martin Aguilar,* participated in data collection and drafting of the manuscript. *Bernabé Canqui-Flores,* participated in drafting of the manuscript and final revision.

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