Design and Economic Evaluation of a Prototype Biogas Plant Fed by Restaurant Food Waste

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Abstract- Food waste and other biodegradable matter in the municipal solid waste stream are a source of environmental and public health concern in cities of developing countries. Anaerobic digestion applied to urban solid organic waste treatment is an option to address those issues and to produce biogas, a renewable energy source. This paper presents the design and economic evaluation of a prototype biogas plant fed by food waste from a restaurant in Mexico City. On average, the restaurant produces 40.5 kg/day of food waste with 23.0% total solids (TS) and 94.2% total volatile solids (TVS). With this amount of food waste, around 69.2 L/day of feeding substrate with 12.7% TVS are produced. Considering an operating temperature of 20°C, total anaerobic digester volume required was calculated at 6.0 m^3. Plant design comprises a continuous stirred tank reactor (1 m^3) coupled with a conventional digester (5 m^3). Organic loading rate and hydraulic retention time were 1.9 kg-TVS/(m^3·day) and 86 days, respectively. The plant is expected to produce 6.1 m^3/day of biogas for use as a cooking fuel at the same restaurant, leading to LP gas savings of 692 kg/year. Plant investment cost was estimated at MXN 129,000 (~9,550 USD). Economic evaluation showed that the biogas plant profitability is highly dependent on LP gas price and its annual growth rate. The prototype biogas plant described here is a step forward in the conception of a biogas facility suitable for cities in developing countries to collaborate in solving their environmental, public health, and energy concerns.

Keywords- biogas plant, restaurant food waste, developing countries, urban areas, profitability indicators

1. Introduction

Municipal solid waste (MSW) generation is a growing worldwide problem. Global MSW generation has been estimated at above 2.0×10^9 tons per year, and it is predicted to increase to 3.0×10^9 tons by 2025 [1]. A major component of MSW is biodegradable matter usually referred to as the organic fraction of MSW (OFMSW). In Mexico, for example, the OFMSW comprised more than 50% of the 38.3×10^6 tons of MSW generated in 2009 across the country [2]. The OFMSW encompasses different organic residues like market organic waste, yard waste and food waste (FW). In case of FW, [3] calculates that about 1.3×10^9 tons of food is lost or wasted annually around the world. Up to 60% of FW is produced at the consumption stage [4], i.e. during food preparation and consumption at households and the food service industry (cafeterias, restaurants, etc.). Food waste demands a proper management due to its potential negative impacts on public health and environment and also to take advantage of its particular characteristics.

For selecting an adequate management approach, waste specific characteristics need to be considered. Food waste features a relative high moisture (74-90%) and volatile solids contents (80-97%, as % of total solids) so biological treatments tend to be preferred [5]. Anaerobic digestion (AD) emerges as one of the most promising approaches for treating various types of organic solid wastes (OSW) including FW [6]–[8]. Through AD, organic compounds are degraded producing both biogas and digested slurry as by-products. Biogas is an alternative, versatile energy source whereas digested slurry can be used as a soil amendment. Copious biogas yields have been reported for FW under different conditions [5], [9]–[12].

Biogas plant design is influenced by various factors such as type of feedstock, operating conditions, and context of implementation. Low-cost, simple design biogas plants appear to be the standard in developing countries. Animal manure is the dominant feedstock and biogas is used for meeting household basic energy needs specially in rural communities [13]–[16]. Further deployment of biogas technology in the developing world, however, depends to a great extent on exploiting feedstocks different from animal manure [16]. Possibilities to explore should include extensively produced OSW such as FW.

Biogas plants fed by OSW exhibit great potential for urban locations in developing countries [17]. Despite a number of small- and medium-size OSW-based biogas units have been implemented [15], these facilities are still uncommon in cities in the developing world. Besides, some of the systems installed have failed due to technical, operational and managerial deficiencies [15]. So, stimulate the deployment of biogas facilities in urban areas requires additional work. A pertinent step in such a direction consists on improving biogas plant designs as to devise functional and cost-competitive configurations.

This paper deals with the design of a prototype biogas plant (PBP) fed by FW from a restaurant in Mexico City, Mexico, to produce biogas for use as supplementary cooking fuel at the same restaurant. Additionally, profitability indicators of the PBP design are calculated and profit-key variables identified. Paper content is organized as follows. Section 2 details methods used to estimate restaurant FW characteristics and production, AD parameters, and biogas generation. Section 3 summarizes assumptions made to compute profitability indicators. Section 4 presents and discusses the results, pointing out the PBP operating sequence, and Section 5 is devoted to the conclusions.

2. Methodology

2.1 Restaurant food waste production and characterization

The restaurant is located in Cuidad Universitaria, central *campus* of Universidad Nacional Autónoma de México (UNAM), in Mexico City, Mexico. Daily food waste production at the restaurant was recorded over a period of seven weeks from Monday to Saturday. Prior to weighting, food waste considered unsuitable for AD, e.g. orange peelings due to their high acidity, as well as inorganic impurities were all removed from collected food waste. Remaining food waste is here referred as cleaned food waste.

Representative samples of cleaned food waste were taken in accordance with Mexican norm NMX-AA-052-1985 [18]. The pH and density of each sample were measured as suggested in Mexican norms NMX-AA-025-1984 [19] and NMX-AA-019-1985 [20], respectively. Total solids (TS), total volatile solids (TVS), and total fixed solids (TFS) concentrations were all determined following standard methods [21].

2.2 Feeding substrate preparation

Feeding substrate was prepared by shredding representative samples of cleaned food waste using a household food waste disposer. While shredding, water was added in different ratios (1.0, 1.5, 2.0, and 2.5 kg of water per 1 kg of wet food waste) to obtain the same number of mixes. By determining TS concentration of each of these mixes, proper dilution ratio to meet wet digestion requirements (10-15% TS) could be found. Based on optimum dilution ratio and average amount and composition of cleaned food waste, the properties and potential volume of feeding substrate were both estimated.

2.3 Anaerobic digestion process

It was assumed that AD process takes place at ambient temperature. Mean ambient temperature in the region where the restaurant is located is around 20°C. Thus, AD process is expected to occur under psychrophilic conditions (5-20°C). Psychrophilic temperature range is seldom used in biogas plant design since mesophilic (20-40°C) and thermophilic (>40°C) conditions are more widely used [16]. Organic loading rate (*OLR*) criterion was adopted to calculate anaerobic digester volume required. This criterion is recommended for substrates with high organic matter concentrations [22]. The *OLR* can be obtained as follows:

$$OLR = \left(Q \times S_0\right) \cdot V^{-1} \qquad (1)$$

Where *OLR* is the organic loading rate in kg-TVS/(m^3·day), Q is the feeding substrate flow rate in m^3/day, S_0 is the biodegradable organic matter concentration in feeding substrate in kg-TVS/m^3-substrate, and V is the effective anaerobic digester volume in m^3. Note that Q and S_0 are obtained from previous cleaned food waste characterization stage.

As stated by the *OLR* criterion, literature was reviewed searching for a reported *OLR* that matched both feedstock and operating conditions of the PBP to use that *OLR* for calculating V by **Eq. (1)**. However, such an *OLR* could not be found so it was estimated through an equation proposed by Safley and Westerman [23]. This equation calculates the *OLR* at a given temperature based on known values of *OLR* and operating temperature from another anaerobic digester:

$$\frac{OLR_2}{OLR_1} = e^{\left[\frac{E\left(T_2 - T_1\right)}{R T_1 T_2}\right]} \qquad (2)$$

Where OLR_1 and OLR_2 are the *OLR* at absolute temperature T_1 and T_2, in K, respectively, R is the ideal gas constant (1.987 cal/(mol·K)), and E is the activation energy constant (15,175 cal/mol as given in [23]). Reference or known values are OLR_1 and T_1, whereas OLR_2 and T_2 correspond to those at desired conditions. Both OLR_1 and T_1 were derived from Tables 15 and 16 in [24], which refer to design features, operating conditions, and performance of a biogas pilot plant fed by hand-selected organic MSW. Consequently, OLR_1 was set at 6.9 kg-TVS/(m^3·day), and T_1 at 35°C (308.15 K). Note that this biogas pilot plant was chosen due to the completeness of its technical and operational reported data as well as to its similarities with the PBP. The OLR_2 obtained by **Eq. (2)** was then used to compute V by **Eq. (1)**. Hydraulic retention time (HRT) in days was calculated as follows:

$$HRT = V \cdot Q^{-1} \quad (3)$$

Effective anaerobic digester volume was multiplied by a factor of 1.3 resulting in the total anaerobic digester volume required. Such a factor was used to take into account additional space related to air and fixtures within the digester.

2.4 Biogas collection, cleaning and utilization

Biogas production rate (Q_{biogas}) in m^3/day was calculated using the expression below:

$$Q_{biogas} = (Q \cdot S_0 \cdot SMP) \cdot (\%CH_4)^{-1} \quad (4)$$

Where SMP is the specific methane production in m^3-CH_4/kg-TVS, and $\%CH_4$ is the methane content of biogas. Theoretically, the PBP should achieve a methane yield similar to that reported for the reference biogas pilot plant, as this was the end of adjusting OLR through **Eq. (2)**. Hence, it was assumed a SMP of 0.39 m^3-CH_4/kg-TVS and a $\%CH_4$ of 56% [24].

Biogas is intended to be used as a supplementary cooking fuel at the same restaurant where food waste is produced. To use biogas as a cooking fuel, at least two impurities should be removed: Hydrogen sulphide (H_2S) and water vapour (H_2O_{vap}) owing to their corrosive action.

Dry adsorption was selected for H_2S removal. In dry adsorption, the H_2S is adsorbed onto iron (III) oxide (Fe_2O_3) forming iron (III) sulphide (Fe_2S_3) and water:

$$Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O \quad (5)$$

An advantageous feature of dry adsorption is that adsorbent agent can be regenerated, i.e. Fe_2O_3 returns to its active oxide form appropriate for H_2S adsorption. The regeneration process normally consists on exposing the adsorbent agent to air so that Fe_2S_3 reacts with O_2 to form Fe_2O_3 and elemental sulphur (S):

$$2Fe_2S_3 + 3O_2 \rightarrow 2Fe_2O_3 + 6S \quad (6)$$

Regeneration procedure can be performed a limited number of times (up to five) before completely replacing the adsorbent agent [25]. The Fe_2O_3 is packed inside a container or desulphurization chamber properly sized to enable an effective contact time. According to [26], the minimum required contact time is 60 s. The upper limit (0.5% by vol. or about 7.6 g/m^3 of biogas) of typical H_2S concentration range in biogas (0-0.5% by vol.) [27] is assumed for calculations. The amount of Fe_2O_3 required for the complete desulphurization of biogas was stoichiometrically determined using **Eq. (5)**.

To remove H_2O_{vap} the simplest way is through condensate traps. Total length of biogas pipeline determined the number of condensate traps to be installed [28]. Concentration of H_2O_{vap} in biogas was estimated based on the operational temperature of the PBP as reported in [29].

Biogas pipeline diameter was defined by consulting a diagram in [30] that relates the biogas flow rate with total length and diameter of biogas pipeline. Additionally, since no biogas compressor was included, biogas pipeline should be rated for low working pressures. Produced biogas is collected in a biogas holder. Type and capacity of biogas holder were selected according to production rate and end use of biogas.

The restaurant currently uses LP gas (LPG) as cooking fuel. All cooking stoves in the restaurant are factory-designed to operate with LPG. Therefore, one of these stoves should be adapted to properly work with biogas. In particular, injector orifice and flame ports of each burner of the stove must be resized. Appropriate size of injector orifice was determined by the following expression [31]:

$$D_{gas_A} \cdot W_{gas_A} = D_{gas_B} \cdot W_{gas_B} \quad (7)$$

Where D and W denote the injector orifice diameter, in mm, and the Wobbe index for gas A (original fuel) and gas B (substitute fuel), respectively. The Wobbe index is a measure of the degree of interchangeability between fuel gases whose value depends on fuel heating value (H, in MJ/m^3) and specific gravity (δ_x, dimensionless):

$$W = H \cdot (\delta_x)^{-1/2} \quad (8)$$

Given that H_{LPG}=93.6 MJ/m^3 and δ_x=2.0, W_{LPG} equals to 66.0 MJ/m^3. For biogas, H_{biogas} and δ_x, and hence W_{biogas}, were computed based on estimated biogas composition.

2.5 Digested slurry handling

It was assumed a TVS removal efficiency of 63%. This figure is the lower limit of TVS removal range (63-69%) reported for the reference biogas pilot plant. Since PBP operating parameters were calculated to attain a methane yield similar to that of the reference biogas pilot plant, the organic matter removal efficiency accomplished by the latter might also be achieved. This assumption takes into account the fact that waste stabilization in AD treatment is closely related to the conversion of biodegradable share of waste into methane [22], [32]. Calculation of digested slurry solid content relied on a mass balance applied to feeding substrate composition and TVS removal efficiency. A residence time of 15 days established the required digested slurry storage capacity.

3. Economic evaluation

Local suppliers were consulted to estimate equipment and installation costs. Fixed cost comprised two different items:

(*i*) a maintenance-related annual cost, and (*ii*) a five-year cost as a sort of re-investment program. The former was assumed to grow at a rate of 3% annually, while the latter remained constant throughout the PBP lifespan. Variable cost, on the other hand, encompassed electric energy, water and miscellaneous expenses. Electric energy supplied to UNAM central *campus* is billed under H-M medium voltage tariff (intermediate hours). Over the period 2002-2012, kWh price for H-M tariff in the central region of Mexico experienced an average annual growth rate of 11.1% [33]. Then, electric energy cost was assumed to increase at such a rate. For both water and miscellaneous costs, a growth rate of 3% per year was considered. Operation-related labour cost and feedstock cost were both omitted.

Plant revenues consisted on cooking-related LPG savings at restaurant resulting from biogas utilization. At the time the economic evaluation was performed, LPG price in Mexico City's region was 11.50 Mexican pesos (MXN) per kilogram of LPG (about 0.25 MXN/MJ). This LPG price was assumed to increase at 15% each year. The PBP should operate at its designed capacity over 260 days per year, i.e. an annual plant capacity factor of 71%. Using a minimum accepted rate of return (MARR) of 6% and a PBP lifespan of 20 years, the following profitability indicators were calculated: net present value, annuity, internal rate of return, benefit-to-cost ratio, and payback period. Lastly, sensitivity analyses were carried out to identify the most influential variables in PBP project profitability.

4. Results and Discussion

4.1. Restaurant food waste

Restaurant's cleaned food waste production varied between 9.0 and 77.0 kg/day, with an average of 40.5 kg/day (**Fig. 1**). Further calculations are based on average production rate. High variability of food waste generation should be attenuated as AD performance is sensitive to regular feeding [7], [8], [34]. Thus, a food waste stream close to restaurant's average production should be assured. In case of waste production deficit, for example, additional food waste might be collected from other restaurants within the *campus*. Physicochemical properties of restaurant's cleaned food waste showed less variability (**Table 1**). Results are consistent with values reported in the literature for similar organic waste [35]. Note that more than 90% of TS content corresponded to TVS, which represent the share of waste matter with higher biodegradable potential.

4.2 Feeding substrate

Despite the restaurant is compelled to segregate its solid waste into organic and inorganic categories, many inorganic impurities were found in collected food waste. This is relevant because poor feedstock quality has been identified as one of the causes of inefficient performance of solid waste-based biogas systems in developing countries [15]. For this reason, the removal of impurities represents the first step in restaurant's food waste pre-treatment.

Once impurities are removed, cleaned food waste is shredded adding water to attain an optimum TS concentration. Proper dilution ratio was found to be 1:1, i.e. 1 kg of water per 1 kg of food waste. The other tested dilution ratios produced too much diluted mixes (TS<10%), which have been associated to low methane yields [32]. Based on cleaned food waste average production and feeding substrate density (1,170 kg/m^3), feeding substrate flow rate (Q) amounted to 69.2 L/day with 12.7% TVS (S_0).

Feeding substrate is collected in a small tank for its homogenization (stirring) and pH neutralization (pH≈7) prior to be processed by AD treatment.

4.3 Anaerobic digesters

From **Eq. (2),** the *OLR* of the PBP should be around 1.9 kg-TVS/(m^3·day), i.e. about one third of that of the reference biogas pilot plant. Corresponding effective and total digester volumes were 4.5 m^3 and 6.0 m^3, respectively, and the *HRT* amounted to 86 days. These values are correlated to the relatively low operating temperature of the PBP.

Total anaerobic digester volume required (6.0 m^3) is provided by two anaerobic digesters in series. The first one, referred to here as *R-1*, is a completely stirred tank reactor (CSTR) digester of 1 m^3. This type of anaerobic digester has been found to be suitable for carrying out the first stages of AD of OSW [36]. Fresh feeding substrate is pumped to *R-1*, where intermittent stirring is applied to prevent stratification and also to favour microbial action. Once *R-1* is full, next time it is fed by fresh feeding substrate a similar volume of pre-digested effluent should automatically flow from *R-1* to the second digester, where AD process is completed.

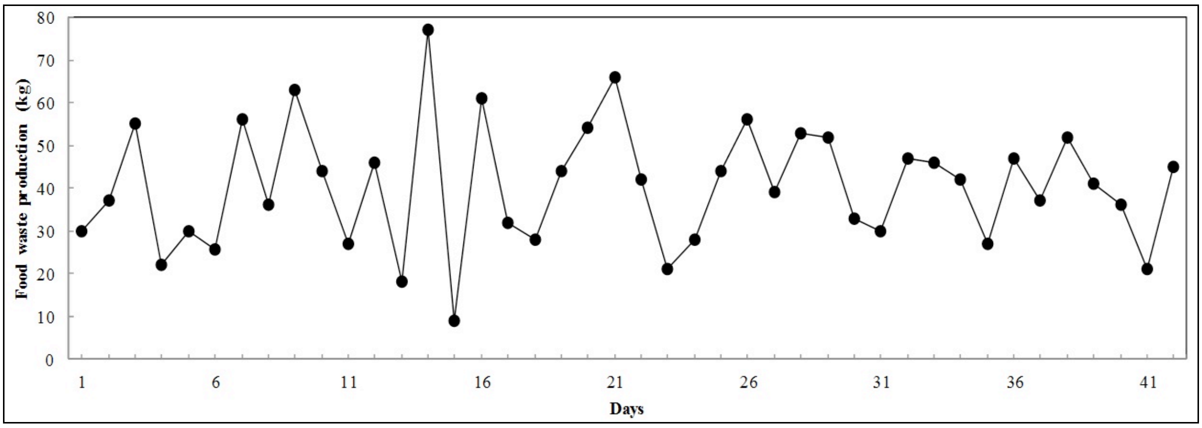

Figure 1. Recorded daily food waste production at restaurant

Table 1. Restaurant's food waste physicochemical properties

Property	Average	Max.	Min.	No. of samples	Stad. Dev.
Density, kg/m^{3a}	715.4	1090.5	459.5	12	194.3
Moisture, %^{a}	77.0	86.8	67.3	24	6.4
TS, %^{a}	23.0	32.7	13.2	24	6.4
TVS, as % of TS^{b}	94.2	96.3	92.3	24	1.2
TFS, as % of TS^{b}	5.8	7.7	3.7	24	1.2
pH	5.7	6.5	3.8	11	1.0

^{a}On a wet weight basis. ^{b}On a dry weight basis.

The second anaerobic digester, referred to here as *R-2*, is a polyethylene tank of 5 m^3 adapted to operate as an anaerobic digester. Substrate in *R-2* is homogenized by pump-aided re-circulation through its inlet and outlet. Because of the larger volume of *R-2*, substrate residence time is larger in *R-2* than in *R-1*. As a result, most of the biogas should be produced in *R-2*.

Both anaerobic digesters are placed aboveground to facilitate plant installation, operation, and maintenance. Unheated anaerobic digesters in low-cost configurations are usually placed underground in part to help stabilize digestion temperature. In case of the PBP, *R-1* and *R-2* are thermally isolated with mineral wool to minimize the effect of ambient temperature variations. Despite temperature might be similar in both digesters, other operational parameters such as pH and *HRT* are likely to differ due to AD stages particular environmental conditions. From this point of view, the PBP might be classified as a two-stage AD system.

Once *R-1* and *R-2* are full, fresh feeding substrate pumped to *R-1* should displace an equal volume of pre-digested effluent from *R-1* to *R-2*. Simultaneously, the same volume of digested slurry leaves *R-2* and is collected in the digested slurry sedimentation tank. Fresh feeding substrate is introduced once a day at least six times a week (semi-continuous feeding pattern).

4.4 Biogas production and end use

Biogas production of the PBP is expected to reach around 6.1 m^3/day. If the amount of food waste processed per day is considered, it results in a conversion rate of about 0.15 m^3-biogas/kg-waste. This figure is slightly above mean value of biogas conversion rate range reported for Indian facilities designed to treat OSW (0.08-0.20 m^3-biogas/kg-waste) [37]. To achieve the estimated biogas production rate, a crucial factor is to feed the PBP by food waste with the highest possible grade of separation.

Biogas pipeline includes one simple tee-type condensate trap. Only one trap is necessary since biogas is likely to present a low H_2O_{vap} content (ca. 20 g/m^3-biogas) due to low plant operating temperature. Complete desulphurization of expected daily biogas production requires around 91.5 g of Fe_2O_3, assuming 80% dry adsorption efficiency. Regeneration is planned to be performed every 12 days. If regeneration is taken to be 100% efficient, then 1.1 kg of Fe_2O_3 should be packed in the desulphurization chamber. Desulphurization chamber is cylinder-shaped with inner diameter 10 cm and height 54 cm to reach at least the minimum contact time for H_2S adsorption. Regeneration is repeated up to five times, and hence adsorbent agent should be replaced every 60 days.

A gas meter is included to record biogas production volume. Biogas is then collected in a 3 m^3 low-pressure biogas holder made of high strength, PVC-coated, polyester tissue. Additionally, the domes of both digesters might store around 1 m^3 of biogas in total. For security reasons, biogas pipeline is equipped with a manometer-relief valve and a flame arrester.

Finally, biogas pipeline is connected to restaurant's stove. Selected stove has moderate energy requirements as it is only used to keep cooked food warm. The stove is composed of three burners of 2.5 kW_{th} each one with 0.8 mm in injector orifice diameter. From **Eq. (7)**, since H_{biogas}=19,990 kJ/m^3 and δ_x=0.94, so that W_{biogas}=20.6 MJ/m^3, injector orifice diameter should be enlarged to approximately 2.6 mm. Similarly, flame ports need to be resized to around 5.0 mm in diameter. Biogas pressure to burners is adjusted by a manually-operated pressure regulator installed right before the stove. Suitable diameter of biogas pipeline was found to be 12.7 mm (0.5 inch).

Daily biogas production should supply around 122 MJ/day. This biogas energy translates into up to 4.5 hours of continuous operation of restaurant's stove. Based on these figures, estimated biogas production meets approximately 6% of restaurant's daily final energy demand for cooking.

4.5 Digested slurry handling

On a daily basis, about 69.2 L of digested slurry should be produced. Given the assumed TVS removal efficiency, TS content of digested slurry was estimated at around 5.5%, comprising 4.7% TVS and 0.8% TFS. Digested slurry is collected in a 1.2 m^3 sedimentation tank to separate liquid and solid fractions. Liquid fraction is directed to dilution and pre-inoculation of fresh feeding substrate. Solid fraction, on the other hand, might be further processed in a compost plant (aerobic treatment) so that it could be used a soil amendment. Complete operational sequence of the PBP is illustrated in **Fig. (2),** while a schematic layout is shown in **Fig. (3)**.

4.6 Economic evaluation

Total investment cost of the PBP was estimated at MXN 129,000 (**Table 2**). Of that cost, anaerobic digesters and civil construction work accounted for over 85%. Economic and technical data of small- and medium-size biogas plants to

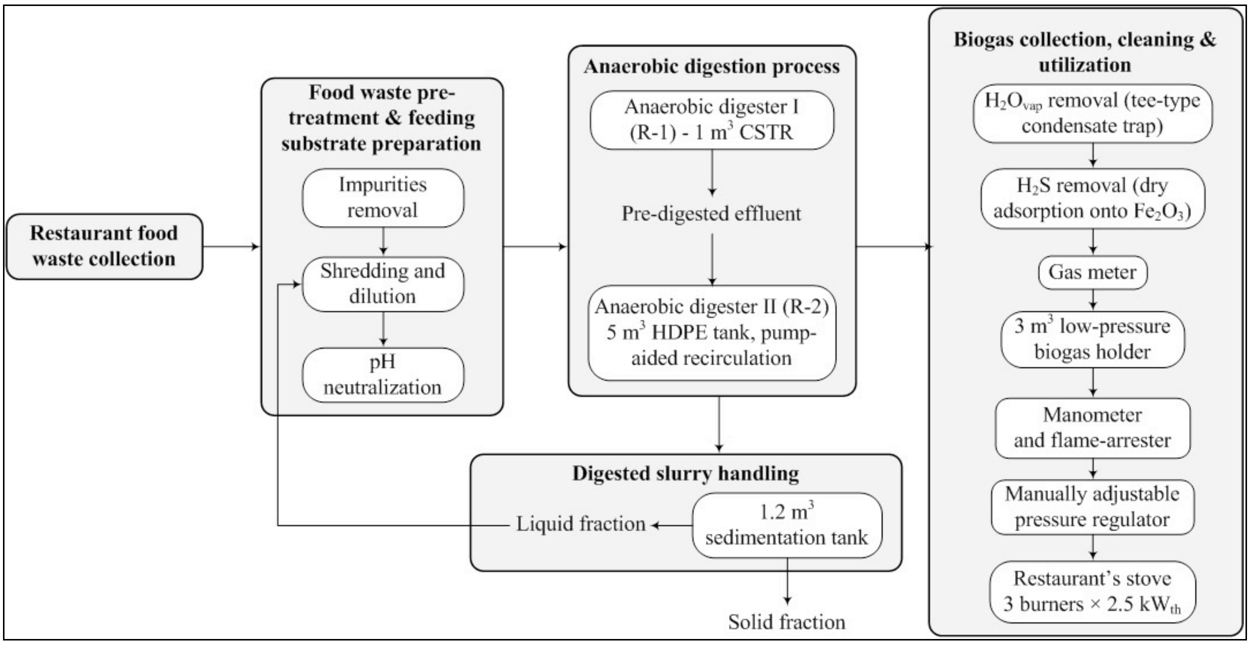

Figure 2. Complete operational sequence of the prototype biogas plant

compare with those of the PBP are scarce in the literature. This denotes the lack of detailed, reliable information that characterizes the topic area of low-cost, solid waste fed biogas units in developing countries [15], [37]. Nevertheless, some data could be found and are used to make comparisons where possible.

Many biogas plants treating OSW in developing countries are based on the floating drum system [15]. Wide dissemination of the floating drum system might be explained in part by the combination of a simple design and the use of inexpensive materials that results in economic advantages. For example, construction and installation cost of a 6 m^3 floating drum type biogas plant has been estimated at INR 23,453 (INR: Indian rupees), almost three-quarters of which corresponds to civil construction cost [14]. This investment cost amounts to approximately MXN 5,000, i.e. around one twenty-sixth of that of the PBP.

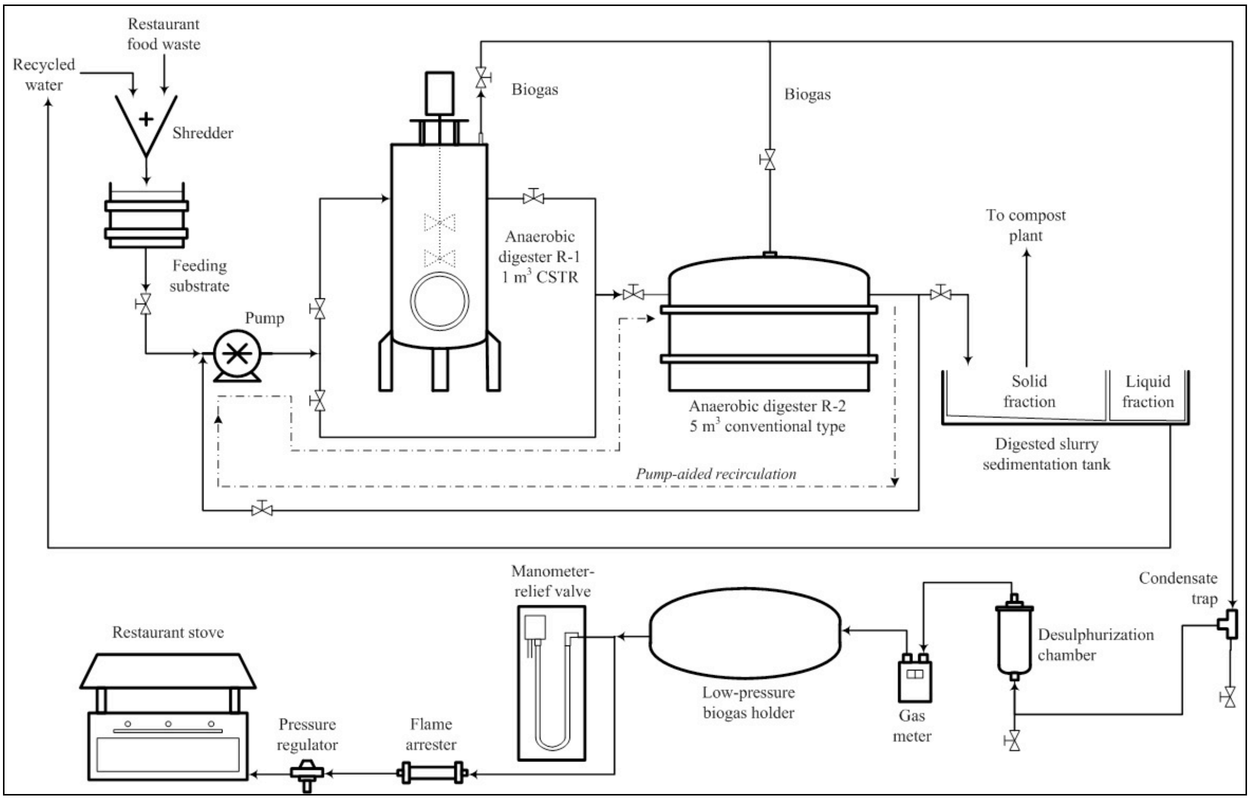

Figure 3. Schematic layout of the prototype biogas plant

Table 2. Prototype biogas plant - main technical and economic features

Item	Estimated value
Annual capacity factor, %	71.0
Annual biogas production	
m^3	1,586.0
GJ	31.7
Utilities consumption	
Fresh water, m^3/year	13.0
Electric energy, MWh/year	2.7
Investment cost	
Waste shredder, MXN	5,350.0
Anaerobic digesters, MXN	31,400.0
Biogas collection, purification & storage system, MXN	8,800.0
Biogas burners, MXN	1,450.0
Civil construction work, MXN	82,000.0
Fixed costs	
Annual fixed cost, MXN/year	1,000.0
Five-year fixed cost, MXN	5,000.0
Variable cost, MXN/m^{3}-biogas	4.1
Revenues (LPG savings), MXN/GJ of biogas	250.0

MXN: Mexican pesos (MXN 13.5≈USD 1)

Nonetheless, operation of low-cost, simple-design biogas facilities usually entails labour-intensive, time-consuming activities [15], [16]. It can be argued that a heavy workload associated to plant operation might turn into a contributory factor to plant abandonment. With this point in mind, the PBP design incorporates some electricity-powered components (waste shredder, substrate pump and stirring device) to facilitate most physically demanding operation-related tasks. Note that powered equipment increases both investment cost and variable cost. This aspect might negatively affect deployment potential of PBP in the economic-restricted, developing world.

Annual biogas production is planned to reach 1,586 m^3, which means around 31.7 GJ per year. This biogas energy production leads to cooking-related LPG savings at the restaurant of nearly 692 kg-LPG per year. Around 2.7 MWh of electricity are annually consumed by plant regular operation, so a net energy production of about 22 GJ/year is anticipated.

Profitability indicators of the PBP project were all positive although modest in magnitude (**Table 3**). For instance, the payback period was close to PBP lifespan, and the internal rate of return was slightly above the MARR. Levelized unit cost for biogas energy (LUC_B) resulted in 0.8 MXN/MJ (ca. 16.0 MXN/m^3-biogas), whereas that for LPG was 1.0 MXN/MJ.

In terms of ton of food waste treated, corresponding levelized unit cost amounted to 2,485 MXN per ton. By comparison, costs for commercial OFMSW anaerobic treatment technologies have been estimated in the region of 62.0-95.0 EUR per ton of waste treated [38], i.e. approximately 1,042-1,596 MXN per ton of waste. It is worth noting that commercial technologies typically achieve lower operating costs than small- and medium size plants due to economies of scale. In addition, cost variations also result from differences in the number and specifications of items involved in the economic evaluation [39].

Table 3. Prototype biogas plant – profitability indicators

Indicator	Estimated value
Net present value, MXN	63,816.0
Annuity, MXN	5,564.0
Internal rate of return, %	8.9
Benefit-to-cost ratio	1.2
Payback period, years	18.0

MXN: Mexican pesos

A sensitivity analysis for the benefit-to-cost ratio revealed that this profitability indicator is highly sensitive to the annual growth rate of LPG price (**Fig. 4**). It was observed that growth rates below 13.1% turn economically unfeasible the biogas plant project. Note that over the period 2002-2012, LPG price in Mexico City actually increased at an average annual rate of 8.3% [40]. This rate is influenced by the Mexican government controlled-price policy applied to LPG and other fossil fuels to improve modern energy access. Another factor that contributes to keep fossil fuel prices low is that price accounting still omits environmental and social externalities of fossil energy. All of this results in unfavourable conditions for massive adoption of alternative energy technologies. Conception of convenient strategies to overcome these economic barriers is out of the reach of this research.

The second most influential variable on the benefit-to-cost ratio was LPG price, followed by annual plant capacity factor, variable costs, and plant investment cost. Observe that only the last three variables are directly linked to the design and operating conditions of the PBP. An accumulative, positive change in these three variables might be necessary to significantly improve the benefit-to-cost ratio.

A sensitivity analysis was also performed for the LUC_B. In this case, the most influential variable was the methane concentration of biogas (**Fig. 5**). Methane concentrations above 46.2% by vol. ensure PBP economic feasibility. Methane content of biogas depends primarily on the type and composition of biomass feedstock [41]. Consequently, to help attain and maintain a profit-making methane level the PBP should be fed by food waste as clean and homogenous as possible. After methane concentration, most influential variables on LUC_B were, in decreasing order, annual plant capacity factor, variable costs, and plant investment cost.

Anaerobic digestion systems for treating waste materials also contribute to reduce expenses related to waste collection, transportation and deposition. Indeed, waste management cost savings might play a key role in the financial viability of anaerobic digestion projects, particularly in large scale ones as reported in [42], [43]. In case of the PBP, however, this source of revenues was not considered since to date the restaurant does not pay any fee

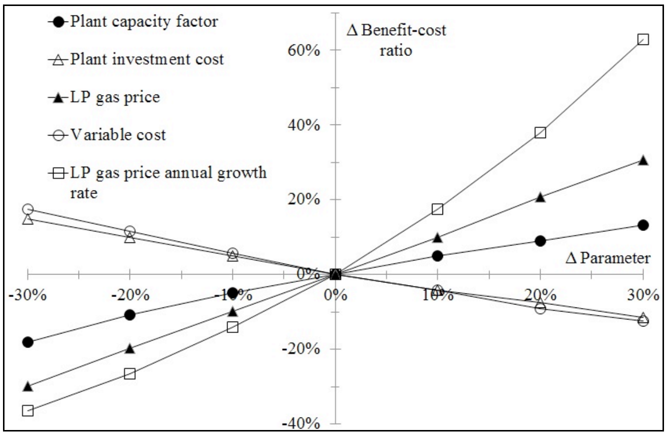

Figure 4. Sensitivity analysis of the benefit-to-cost ratio

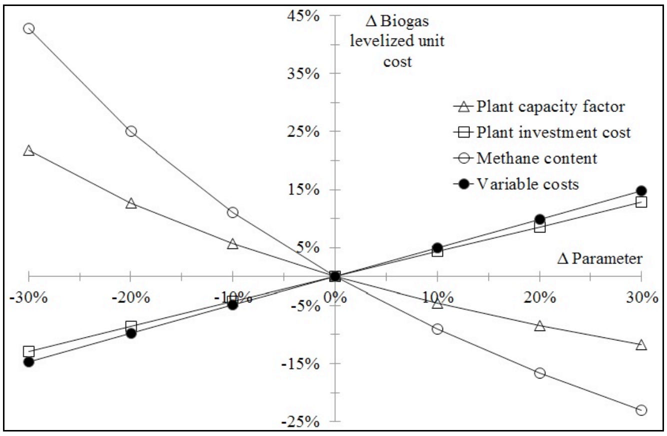

Figure 5. Sensitivity analysis of levelized unit cost of biogas

specifically for the collection and deposition of its solid waste. It is clear that a charge like that would enhance the economic profitability of the PBP.

Implementation of the PBP reports environmental benefits as well. On an annual basis, over 10.5 tons of restaurant food waste is deviated from final disposal sites. Besides, greenhouse gases emissions (GHG) are cut by as much as 14.5 tons of CO_2 equivalent (CO_2e) per year. This last figure comprises avoided emissions from both proper food waste management, i.e. impeding the uncontrolled release of methane from waste decomposition, and LPG substitution. The former amounted to 12.5 tons of CO_2e per year, while the later to 2.0 tons of CO_2e per year.

5. Conclusions

Urban areas in developing countries generate massive amounts of solid waste that require integral management schemes to tackle associated environmental and public health concerns. A large fraction of urban waste stream consists on biodegradable organic matter such as food waste which can be treated by anaerobic digestion to alleviate those adverse impacts and obtain biogas as by-product.

The present work details the design of a prototype, small-scale biogas plant fed by food waste from a restaurant in Mexico City. The restaurant generates on average 40.5 kg of food waste per day which provide 69.2 L of feeding substrate with 12.7% TVS that is processed by the plant to produce 6.1 m^3 of biogas with 56% CH_4. The plant features two anaerobic digesters in series (1 m^3 *CSTR* coupled with a 5 m^3 conventional digester) working at ambient temperature with *HRT* of 86 days and *OLR* of 1.9 kg-TVS/(m^3·day). Biogas produced meets around 6% of restaurant's final energy demand for cooking and allows LPG savings of 692 kg annually. A modified stove of the restaurant uses the biogas to continuously operate up to 4.5 hours.

Operational temperature of the prototype plant is low compared to typical values used to design biogas systems in tropical regions. As a result, longer digestion time and lower processing rate are necessary, which in turn influence equipment specifications such as digester volume required. The plant includes some powered components to assist in hard manual labour operation-related tasks (e.g. digesters loading and stirring) at the expense of increasing investment and operational costs and probably affecting plant's potential market especially in low-income countries.

Profitability indicators point out that the plant project is economically feasible although close to minimum acceptable limits. Besides, it is highly dependent on LPG price and its annual growth rate. In this sense, inadequate fossil fuel pricing policies might pose an economic barrier to implement biogas facilities as well as other renewable energy technologies. However, as economic conditions are site-specific, profitability assessment will vary from location to location. What is more, additional environmental and social benefits should also be considered to foster renewable energy deployment. In the case of the prototype biogas plant, up to 10.5 tons of food waste avoids final disposal sites and 14.5 tons of CO_2e are cut on an annual basis. Despite these contributions seem to be modest, they would be substantial if multiple biogas plants were installed and operated in multiple sites.

As future work, it is necessary to carry out supplementary processing trials to corroborate these preliminary results as well as to evaluate possible applications for digested slurry. Additionally, plant layout might be modified to some extent aiming at reducing the investment cost and hence, improving its cost competitiveness. This prototype biogas plant sets some elements to conceive a solid waste-based biogas facility suitable for cities in the developing world as a mean to positively change living conditions in these human settlements.

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