Techno-Economic and Environmental Assessment for Biomethane Production and Cogeneration Scenarios from OFMSW in Mexico

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Abstract

Mexico City is one of the largest cities in the world and therefore there is a high generation of waste, of which 44% is equivalent to the Organic Fraction of Municipal Solid Waste (OFMSW). In this work, a characterization of the household OFMSW was carried out, and two case studies were evaluated for the application of biogas production by anaerobic digestion process using OFMSW. CASE I considers obtaining biomethane, while CASE II involves energy cogeneration. An economic and environmental evaluation was carried out on different amounts of OFMSW (100–500 MT). The net present value (NPV) of this project (CASE I, NPV = − US$18,915,067/year and CASE II, NPV = − US$28,636,890/year) does not show the viability of the process, unless the support of a subsidy is considered. The value of the subsidy to find NPV = 0 is 5.64% for CASE I and 6.84% for CASE II, on the total investment at 200 MT of OFMSW. On the other hand, the Waste Reduction (WAR) analysis algorithm was used to determine the potential for environmental impact (PEI). This criterion considers the indexes of eight categories, where CASE I = 574,820 PEI/year and CASE II = 570,479 PEI/year. The in-depth research of this work helps to maintain the anaerobic digestion process in a circular economy context.

Graphic Abstract

Extended author information available on the last page of the article
Statement of Novelty

The innovation of this research is to find the economic feasibility of the anaerobic digestion process in Mexico at different scales of Organic Fraction of Municipal Solid Waste treatment. For large projects such as biogas production, in addition to determining economic criteria, it is important to find the subsidy value needed to achieve feasibility. The environmental impact was carried out using the WAste Reduction (WAR) methodology and it was integrated with the economic assessment, approaching in a more complete way the viability of the process. This work seeks to establish technical criteria and economic indicators that allow the public and private sector to establish strategies for the development of this type of projects Mexico or in countries with similar contexts.

Introduction

The management of municipal solid waste has become a problem due to population growth. If this problem is not addressed, public health and environmental protection problems can result due to climate change, loss of resources and land use. There are different options available to manage solid waste, one of which is waste-to-energy conversion. However, factors such as population, socioeconomic status, climate conditions, installation cost, recurring cost, cost–benefit analysis and environmental assessment must be considered before its proposal. Good management of Organic Fraction of Municipal Solid Waste (OFMSW) must cover the waste generated by various sources, such as commercial, industrial, institutional and municipal services. There are certain factors which prevent the development of infrastructure in treatment technologies such as management and confinement of OFMSW in developing countries like Mexico.

On a global scale, 70% of municipal solid waste is deposited in landfills, 19% is recycled and only 11% is utilized in waste-to-energy conversion schemes and this occurs due to logistic and economic problems, such as shortage of primary fossil energy and volume restriction in landfills [1]. Municipal solid waste generation in Mexico City is more than 12,000 MT (Metric tons) per day and 44% of the generated waste corresponds to OFMSW [2], estimating a yearly percentage of the main sectors: household (47.7%), commercial (15.4%), services (13.6%), markets (10.6%), Supply Central (4.6%), miscellaneous (5.1%) and controlled (3%) [3]. In Mexico City, open landfills are the most common method of treating OFMSW with a high percentage of organic components in developing countries because the cost is lower. However, open landfills and poorly designed landfills may pollute shallow and underground waters, causing public health risks. Meanwhile, lack of availability and the rise in the cost of land near urban areas have made landfills increasingly expensive and impractical. As an alternative, the anaerobic digestion process (ADP) is frequently the most profitable method due to the high energy recovery and its limited environmental impact [4]. There are other alternatives such as composting since its investment cost is lower, however, its operating cost is higher, especially as the size of the plant increases [5]. Research has also been conducted to compare the techno-economic and environmental feasibility of ADP with respect to thermochemical processes such as incineration, pyrolysis, gasification, and hydrothermal carbonization. Among the advantages of thermochemical methods, it stands out that they do not require pretreatment of the substrate and complete sanitization of the waste can be achieved, but in these cases, except in hydrothermal carbonization, the moisture content can considerably reduce the performance of the process. Another disadvantage is that with respect to ADP, these processes require a high energy demand and adequate treatment of atmospheric emissions in the case of incineration [6, 7]. ADP is not a novel technology as it has been used in much of the world for many years. However, the application of ADP in OFMSW is still relatively limited. This is due to its high solids content, large particle size, slowly biodegradable components (lignin-rich woody waste), and the heterogeneous nature of the waste, making process control difficult [8]. Grand scale digestors (i.e. hundreds to thousands of cubic meters) are historically more popular in developed countries, as they require bigger infrastructure and large capital investment. In most cases, the biogas produced is used for combined heat and energy applications and is sometimes upgrading to be used as transport fuel [9]. However, large-scale application is necessary for countries that are large generators of waste. The main challenges in waste management as OFMSW are: (i) It is preferable to dispose of OFMSW through traditional landfills, mainly due to financial, social and technical factors (although the negative impact on the environment is greater); (ii) tipping fees at landfills are relatively low; (iii) challenge in the management and planning of the most efficient technologies; and (iv) difficulty in leachate recirculation and gas recovery in sanitary landfill. In addition to these challenges, it must be considered that the impact of improper handling of this type of waste can cause spread of...
epidemic diseases and threat to human health, and emission of greenhouse gases into the environment due to decomposition of organic waste [10]. In the specific case of ADP, yield is usually affected by the effect of organic toxins (such as chlorophenols, halogenated aliphatics and long chain fatty acids), inorganic toxins (ammonia, sulfur and heavy metals, among others) and emerging nanomaterials on the anaerobic digestion [11]. Due to the fact that household OFMSW covers a high content of the waste generated, the study of its treatment is of interest. FORSU is a highly heterogeneous substrate, as its physicochemical and bromatological characteristics are influenced by different factors such as geographic location, number of inhabitants, gastronomic culture, season of the year, economic activities, purchasing power, and even the collection method [12]. However, there are general characteristics that can be extrapolated around the world. According to an analysis by Fisgativa et al. [13] carried out from 70 investigations, this substrate is characterized by a moisture content of 74 to 90%, a volatile solids fraction of around 88±8.2% and an average acidic pH of 5.1±0.7. The typical FORSU is composed mainly of degradable carbohydrates (41–62%), proteins (15–25%), and lipids (13–30%). In general, it has variable proportions of nutrients and micronutrients, although it has a relatively low C/N ratio, which varies between 13.2 and 24.5, as well as low levels of heavy metals. Household OFMSW is not a uniform fraction by its nature and origin, whose typography depends on its composition, which is subject to diet, seasonal changes and a whole series of factors conditioning the generation of household OFMSW. This fraction contains large amounts of water and organic matter, such as vegetables, fruit, sugars, fats, and proteins. With these nutrients it is susceptible of being broken down by microorganisms, creating leachates that produce bad odors as byproduct of biodegradation.

Despite the benefits found in ADP, there are factors that prevent its use in developing countries like Mexico. These factors imply high operating and investment costs. In addition to generating low secondary income as in the tipping fee, where there are no specific costs for the management and confinement of OFMSW in Mexico. However, some data collected shows that the cost varies between US $5/MT and US $15/MT [14], while in first-world countries like the United States, tipping fee is between US $24–US $70/MT [4]. Another factor that might contribute to the economy of ADP, is the digestate and it can be sold as fertilizer. In some countries such as Ireland, it is worth approximately US $45/MT [15].

In spite of some economic impediments, Mexico City has the potential to generate 12,500 tons of Municipal Solid Waste and which through biological methods like ADP, can be transformed into biofuels such as methane, helping vastly with the growing production of waste and the lack of sites [16]. The experience of many countries shows that biogas can be successfully utilized for different proposals, such as energy generation, direct use, heating, and as an alternative to transport fuel, among other applications. ADP can produce biogas that implies the breakdown and stabilization of organic materials in anaerobic conditions by microbial organisms [17]. There are different ways to use biogas. On the one hand the biogas can be purified mainly by an absorption column. Biogas is considered to have a lower heating value in comparison to natural gas (22 MJ/Nm$^3$ as opposed to 31–40 MJ/Nm$^3$), and this is because CH$_4$ concentration in biogas is generally lower (40–70%). Therefore, biogas must be concentrated at 97–99% CH$_4$, and CO$_2$ can be diluted in water in an absorption column, whereas natural gas contains around 75–99% methane, 0–25% other components such as alkane, propane, butane, among other compounds. Hence, biomethane is similar to natural gas in regard to gas quality [18]. Biomethane can be used as an alternative to natural gas [19] and can be injected into the natural gas network, which permits its distribution over longer distances, or it can be compressed and used as transport fuel (bio-GNC) for vehicles adapted to use compressed natural gas.

Alternatively, biogas can be utilized to generate heat or steam in a tank, where the most common use of biogas is for generating electricity and heat in a combined unit. Vasco-Correia [9] mention that in this way the process is more efficient, achieving energy cogeneration. Biogas works as steam-generating fuel and the heat generated, as well as the electricity, is integrated to devices of the same process. Finally, the excess electricity is the main income, and it is sold to contribute economically to the process.

In Mexico, the generation of clean energy from renewable resources represents less than 16% and the total installed generation capacity in the country is 53,114 MW, ranking Mexico as the seventh in the world. It is estimated, however, that an additional capacity of over 20,000 MW would be needed to face the growing demand expected [20]. Therefore, it is necessary to opt for technologies like ADP that help in the treatment of waste and can add to the energy demand. In Mexico, there are facilities that employ ADP to generate biogas in wastewater treatment plants, pig farms, and milking cowsheds. Still, in the treatment of OFMSW through ADP, there are very few industrial and municipal level plants. Municipalities have not managed to handle solid waste due to financial factors, and the economic instruments have hindered the offer of adequate waste management services. There are studies that are interested in determining the economic [6, 21, 22], environmental [23–27] or both [28, 29] viability of ADP. ADP studies have been carried out in Mexico where the interest is inclined in the technical part of the process, that is, obtaining yields, productivity, process design or study about the types of waste [2, 30–32]. There are other studies that determine the environmental assessment for ADP. The Ramírez-Islas [33] work team
carried out an LCA for the treatment of anaerobic digestion at medium-scale, to produce energy through the treatment of pig manure. On the other hand, Rivas-García [34] carried out an environmental assessment on milk production for three manure management scenarios. They concluded that manure management systems with anaerobic digestion can improve the environmental profile of milk produced. On the other hand, few studies have been carried out on an economic evaluation for ADP. Tsydenova [35] evaluated the treatment of municipal solid waste (MSW) from the wholesale market Central de Abasto using anaerobic digestion. Identified barriers to feasibility of energy generation through biogas of MSW in Mexico include the need for large investment, low profitability through sales of electricity, and support incentives are needed to promote the use of by-products (energy and digestate). Chan Gutierrez [36] concludes that biomethane production could compete with natural gas if a subsidy is available. However, according to the knowledge of the authors, there are no studies that integrate an evaluation of the economic and environmental feasibility for full-scale projects of ADP for biomethane production and generation of electricity in Mexico City, using household OFMSW.

The present study investigates for the first time the ADP of a full-scale stage, using household OFMSW because it is one of the main wastes in the metropolitan area of Mexico City. For this, a methodology was used where the residues (household OFMSW) were characterized, obtaining its formula and some characteristics such as humidity, Volatile Solids (VSS), Fixed Solids (FSS), among others. According to this information, the theoretical yield of biogas production was determined, which allowed to carry out a techno-economic and environmental evaluation to treat 100–500 MT of OFMSW, considering a case that describes the production of biomethane and another in which it is considered cogeneration of energy. This was based on a wet ADP pilot plant that treats 600 kg/day of OFMSW. In this way, the analysis of the process design will evaluate the technical criteria, affect the economic profitability of the process along with other variables such as investment costs, operating costs and income, complemented with the study of environmental impact categories.

Materials and Methods

General Methodology

The anaerobic digestion pilot plant (main basis of this research) has an OFMSW treatment capacity of 600 kg per day and is designed to operate 360 days per year and 24 h a day. In order to acquire a plant that treats greater OFMSW capacity, economic evaluations are being carried out applying the same process design to find a profitability of the Anaerobic Digestion process in Mexico City. Therefore, for the ADP study, the aim is to treat around 3–10% of the total OFMSW in Mexico City. In this way, the investigation was conducted for the treatment of 100–500 MT of OFMSW. Small scales are usually reported for ADP [37–40]. However, some other studies report large-scale process sizes, where the volume of the digesters can be greater than 2000 m³ [41–45]. To carry out the scaling, the principle of similarity was used. This principle refers to the relationship that exists between physical systems and their size, being basic in the scaling of physical and chemical processes [46]. The data that were considered were the biogas production, the operating time and part of the information in the flow diagram. This research work seeks to expand the knowledge of the process at different scales of OFMSW treatment, and to find a greater economic and environmental feasibility through analysis and simulation, considering national conditions such as conventional modus operandi and operating costs.

The general methodology applied to this study is shown in Fig. 1. With samples obtained from household OFMSW, a characterization was performed with the objective of knowing the physicochemical properties of the waste and finding the benefits of biogas-biomethane formation on the decomposition of OFMSW, mainly. The experimental values are used for an economic and environmental impact analysis of the process.

Two case studies were performed, both of which assess the technological routes to produce biomethane and generation of steam and power, shown as follows:

(i) CASE I considers the production of biogas, which is purified mainly by means of an absorption column, obtaining a 97% purification of biomethane for sale. Within this case study, the integration of heat in the equipment, such as the anaerobic digester and sludge drying, is contemplated.

(ii) CASE II considers steam and power generation. It considers the integration of heat to equipment such as the anaerobic digester and the sludge dryer, in addition to the electrical energy used for the process. Excess electricity is sold and is considered the main income.

For this part of the study, in order to have a better understanding of the process, a modular simulator was used as a tool that allows determining the input and output values of matter and energy flow of the process, cost analysis of each equipment and used as a precursor for the development of an environmental analysis. This can be achieved as the simulator offers a database of the properties of the components, unitary operations and equations for each one of the operations of the process. To be able to do the study, a flow diagram was required created in the SuperPro Designer v.11.
simulator. Likewise, the simulations used the equations of state to determine the activity coefficients with the non-random model of two liquids (NTRL), while the fugacity coefficients of each of the species that are involved in the process were calculated by means of the Peng Robinson equation.

Characterization of OFMSW

The municipal solid waste collection was collected from the municipality of Naucalpan de Juarez. This municipality is located in the southern part of the State of Mexico located between the geographic coordinates of 19° 28' N latitude and between 99° 14' W longitude. The total land area that covers the municipality of Naucalpan de Juárez is about 149.86 square kilometers.

The waste samples showed organic and inorganic residues. Inorganic materials such as metals, plastic bottles, plastic bags, nylon and other materials were separated, as well as large pieces of organic matter such as bones and some garden products. Only organic matter was used, while inorganic matter was rejected and separated. For the methodology used in the sampling of the residues, the method corresponding to the Mexican standards NMX AA-015-1985 is applied. For the characterization of the waste, the standard method of quartering was used for the analysis of water and wastewater, implemented by the American Public Health Association [47]. The characterization of the samples used in this study was carried out on a wet basis, in this way the stability of the substrate is ensured. Volatile solids and Fixed solids were determined from crushed OFMSW samples by the APHA 2540-E method. Total solids (TSS), pH and moisture via the APHA 2540-B method. Total Kjehldahl nitrogen (TKN) through the 4500-Norg B method, ammonia nitrogen (NH₄-N) using WPCF 4500-NH₃ and total phosphorus (TP) by means of APHA 4500-P–C. In this study, the samples have a moisture percentage of approximately 90%. This allows an adequate medium for metabolic reactions to occur in anaerobic digestion, achieving better diffusion of the substrate. Part of this information was taken by Yang [48], because it ensures that at a high percentage of moisture, a lower amount of inoculum is required.

According to a previous elementary analysis for household OFMSW, theoretical methane production yield was determined with a stoichiometric approach making use of the Buswell and Boyles equation [28]. This equation was modified by Boyle from the original equation for the resolution shown in Eqs. (1–4), because values are required for nitrogen and sulfur as reactants, which are part of the
reaction products of ammonia and hydrogen sulfide. The reactions are as follows:

$$C_aH_bO_cN_dS_e + xH_2O \rightarrow yCH_4 + zCO_2 + dNH_3 + eH_2S$$  \hspace{1cm} (1)

where

$$x = a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}$$  \hspace{1cm} (2)

$$y = \frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}$$  \hspace{1cm} (3)

$$z = \frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}$$  \hspace{1cm} (4)

The biochemical reaction is balanced and can be applied to any input with known relative proportions of carbon, hydrogen, oxygen, nitrogen, and sulfur. The model assumes that these elements are the only components of the raw material [28].

**Techno-Economic Assessment**

**Process Analysis**

For CASE I (purification and sale of biomethane) and CASE II (cogeneration) presented in this work, a single-stage digestion process was considered, with a continuous operation and stirring regime, supplying 100 to 500 MT/day of OFMSW. Eq. (1) plays a very important role because it determines the performance of the biogas production in the digester. The anaerobic digestion was wet, that is, a percentage of total solids of 10% and mesophilic conditions (35 °C) were required. The pH in the reactor was controlled by adding NaHCO₃ to maintain its operation in a range of 6.5 to 7 and the hydraulic retention time (TRH) was 21 days.

On the other hand, a solid–liquid, effluent called digestate, which, for this particular case, coming from a wet process has a large amount of water, requiring the use of a cationic flocculant to separate the solid fraction suspended, same that can be commercialized as a soil improver. Thus, the sludge is dried and can be considered for sale as compost. On the other hand, the concentration of hydrogen sulfide (H₂S) that is part of the biogas is toxic and corrosive. For CASE I, an absorption column was used by a high-pressure physical water scrubbing (HPWS) process. This technology was selected because it allows a methane concentration > 97%, mainly eliminating CO₂ and H₂S. In addition, it has the advantage that it does not require handling or special chemicals, being easy to operate with low methane pressure losses (<2%) and the water used in the process can be regenerated [49]. Finally, it is important to mention that even though there are emerging biogas improvement technologies, especially of the in situ type, physical absorption with water continues to be the most widely used biogas purification system in the world in industrial-scale plants. According to Khan et al. [50] in Europe for example, of the 428 biomethane producing plants, 152 use water scrubbers (35%), 88 chemical scrubbers (20.5%), 88 membrane (20.5%), 72 pressure swing adsorption (16.8%), 20 organic physical scrubbers (4.6%) and 7 other technologies (1.7%). About 41% of the biogas upgrading plants in the world employ water scrubbing technology.

Hence, it must be removed from the biogas as part of its purification. H₂S is the most problematic pollutant and it can be eliminated by chemical reaction with some ferrous material such as iron oxides (Fe₂O₃ or Fe₃O₄), zinc oxide (ZnO), alkali solutions, etc. [51]. For this work, the chemical reaction with Fe₂O₃ described below was used:

$$Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O$$  \hspace{1cm} (5)

The resulting products must be disposed of safely, leading to additional costs and environmental concerns. The technical data of the most relevant equipment in the study of the process, such as hours of operation, steam feed rate, heat transfer agent, among others, are shown in Table 1.

**Economic Analysis**

Biogas plants require important capital investments, careful planning and financial foresight. Complete financial modelling of these complex biogas projects is fundamental to obtain a realistic image of their economic feasibility. Operating cost, financing cost of the project and cash flow planning

| Concept                        | Value   | Unit     |
|-------------------------------|---------|----------|
| Hours of operation            | 8400.00 | h/year   |
| Amount of processed OFMSW     | 100–500 | MT       |
| Digester                      |         |          |
| Digester temperature          | 35.00   | °C       |
| Power consumption (Agitation) | 0.01    | kW/m³    |
| Heat Transfer Agent (Steam)   | 152.00  | °C       |
| Steam feed rate               | 75.33   | kg/h     |
| Sludge drying                 |         |          |
| Evaporative efficiency        | 77.53   | %        |
| Operating evaporating capacity| 7456.06 | kg/h     |
| Temperature                   | 60.00   | °C       |
| Absorption column             |         |          |
| Total specific area           | 190.00  | m²/m³    |
| Nominal diameter              | 0.025   | m        |
| Critical Surface tension      | 0.040   | N/m      |
| Column diameter               | 52.00   | m        |
are essential components to guarantee the smooth realization of the biogas project and measure the investment return [18].

Technical study of ADP, such as balances of matter and energy, equipment, etc., allows for the study of an economic analysis, considering the costs of raw materials, equipment, use of heat transference agents and operation, as well as income such as biomethane sale or electricity generation. The economic parameters are suggested for the year 2020, in a building period of 30 months, project lifespan of 10 years considering a 4% inflation. Profitability measures play an essential role in the selection of concept design alternatives resulting from ADP. The economic criteria considered to evaluate profitability are the payback period (PB) described in Eq. (6) and the net present value (NPV) described in Eq. (7). These criteria are often used as preliminary estimators for the study of flow charts or different design configurations. PB is the time required for the annual profit to equal the original investment. Since it is simple and even more understandable than other criteria, it is widely used in early evaluations to compare alternatives to other processes.

\[
PB = \frac{C_{TDC}}{(1 - t)(S - C) + D} = \frac{C_{TDC}}{\text{net earnings} + \text{annual depreciation}}
\]

where \(C_{TDC}\) is the total depreciable capital, \(t\) is the sum of the tax rate, \(S\) is annual sale income, \(C\) is annual production cost and \(D\) is annual depreciation [52].

NPV contemplates cash flow discount to the current value. Then, the sum of all the discontinuous cash flow is NPV.

\[
NPV = \sum_{i=0}^{n} \frac{Q_i P_i}{(1 + r)^t} - \sum_{i=0}^{n} \frac{C_i}{(1 + r)^t}
\]

where \(Q_i\) and \(P_i\) are production volume and initial price in period \(t\), respectively. \(C_i\) is total net cost (it represents initial cash flow without \(B_i\) in period \(t\)) and \(r\) is bank interest rate [53].

Positive values for NPV (NPV > 0) indicate that the process is profitable. The higher the NPV value, the more confidence there could be to invest in the process. The same occurs with PB, only in this case the shortest time possible is sought. Suggested PB to consider an investment is 4 years [52]. Economic data of costs and profits for the study of the process are shown in Table 2.

### Environmental Analysis

In this analysis the WAR (WAste Reduction) algorithm was used, designed by the United States Environmental Protection Agency (USEPA) [54]. This algorithm is based on the potential environmental impact (PEI) index. PEI represents the total impact that mass emissions would have on an ecosystem. were they released into the environment. The analysis considers 8 impact categories divided into two areas: toxicological (HTPI, Human Toxicity Potential by Ingestion; HTPE, Human Toxicity Potential by Exposure; TTP, Terrestrial Toxicity Potential; and ATP, Aquatic Toxicity Potential) and atmospheric (GWP, Global Warming Potential; ODP, Ozone Depletion Potential; PCOP, Photochemical Oxidation Potential, and AP, Acidification Potential). One way to determine the value of each category is through indexes [55]. Therefore, PEI is the pondered sum of every individual impact index of each chemical compound for the possible categories and determined as follows:

\[
PEI = \sum_{i=1}^{n} \alpha_i \psi_i
\]

where \(\alpha_i\) is the main factor for each of the \(i\) categories, \(\psi_i\) is the potential environmental impact for each category. In this study, the considered sum of all factors in the different categories is 1, where the equivalent main factor was applied to every category (\(\alpha_i = 0.125\), granting them equal importance. For this study, PEI is expressed in terms PEI/year of the main byproduct. The lower the global impact index of the process, the more favorable for the environment it is. This analysis applies to both case studies, which helps to determine which of them has lower impact potential. It is important to mention that this methodology only shows the environmental impact due to the input and output streams, as well as the components of the process. It is very helpful for comparing the impact on different types or process designs.

### Results and Discussion

#### Characterization

The characterization of OFMSW is necessary, considering real values such as the amount of solids for the study of the process. This information was necessary to determine the
empirical of OFMSW formula on 14 samples that were taken from household waste. ADP can work with different contents of TSS. However, it is common that most large-scale ADP are operated with TSS contents of less than 15%. Therefore, it is suitable for the treatment of high moisture waste such as sewage sludge, food waste, and animal manure [48]. Table 3 shows the physiochemical properties of household OFMSW, specifying the amount of solids and nutrients that were determined for anaerobic digestion.

The waste fraction presented a large amount of fruits and vegetables, corresponding to 21.7% and 45.5%, respectively. It also contains 3.5% of meats, 1.6% of leftover food and 20.6% of the remaining organic waste. While it contains only 5.9% of inorganic material and 1.2% of leachates. Only organic matter was used, while inorganic matter was rejected and separated, as mentioned above. By separating the inorganic material, OFMSW functions as a feedstock for anaerobic digestion to occur due to its readily biodegradable nature. In addition, the waste contains high levels of moisture, which is recommended to be between 75 and 90% for wet digestion [57]. The moisture percentage is similar when compared to that of other wastes shown in Table 3. However, the value is within the recommended range, which allows wet anaerobic digestion. The samples present acidity (pH close to 3.26), so it is necessary to add sodium bicarbonate (NaHCO₃) until a neutral pH is reached to ensure suitable feed conditions for this type of system [30]. VSS percentage regarding TSS often varies between 70 and 95%. VSS destruction is a sign of the efficacy of the anaerobic digestion process. VSS/TSS relation was 88.7%, which indicates a high biodegradability of the substrate, presenting a slightly higher percentage compared to other studies (Table 3). These properties of OFMSW were considered for the ADP study. With the values obtained from the characterization, the empirical formula C₅₃₁H₉₇₂O₄₇₄N₂₀S was obtained, which is used as a fundamental part of the study of the anaerobic digestion process, since it determines the theoretical yield used in the simulator for the economic and environmental impact evaluation.

### Techno-Economic Profitability

#### Process Analysis

The production process described in the Techno-Economic Assessment section, an annual operating time was considered of 8,400 h (350 days) in a continuous process, as well as a construction period of 30 months, a Startup period of 4 months and a Project lifetime of 15 years, i.e., approximately 18 years evaluation time. The flow diagram is shown in Fig. 2. The hydraulic retention time in the digester (RBH-01) is 21 days, working at a volume of 4,750 m³ to treat 200 MT/day of OFMSW. An analysis was performed at different OFMSW treatment capacities, shown in Table 4.

Part of the characterization is indispensable for the determination of VSS. This value is required to know the appropriate amount of household OFMSW inflow to consider. That is, 8.87% of the total amount of household OFMSW is contemplated, while there is 90% moisture. Thus, in the S-107 flow an amount of 14,440 Nm³/day (17,309.4 kg/day), achieving a yield of 72.2 Nm³ biogas/MT OFMSW (backed by similar results in the pilot anaerobic digestion plant).

The empirical formula (obtained in the characterization of OFMSW) for the theoretical methane yield based on the Buswell-Boyle equation is described in Eq. (9):

\[
C_{531}H_{972}O_{474}N_{20}S + 66.5H_2O \rightarrow 19.3NH_3 + 270.2CO_2 + H_2S + 260.7CH_4
\]

A major part of the components contained in household OFMSW are soluble and insoluble crude fibers (such as cellulose, hemicellulose and pectins) and starches that represent the main carbohydrates [58]. As mentioned, household OFMSW is expected to achieve high degradation due to the amount of carbohydrates. However, it can achieve low yields when using these substrates because of the crude fibers containing lignin, which is related to crude fiber polysaccharides in foods and increases resistance to digestion by forming lignocellulosic complexes with cellulose and hemicellulose. On the other hand, the production of hydrogen sulfide in ADP is not desirable. Proteins with sulfur are part of some foods that can be found in these residues such as eggs, fish and meat. These proteins can degrade rapidly increasing ammonia, causing inhibition in the production of biogas [58]. Kumar [8] mentioned that sometimes there are low yields (such as 60 Nm³/MT of OFMSW) due to the type of waste, or complications within the process.

### Table 3 OFMSW Physicochemical Properties

| Parameter     | Value (This work) | Valuea [12] | Valueb [56] | Valuea [8] |
|---------------|-------------------|-------------|-------------|------------|
| Moisture (%)  | 90.0              | 70.3        | 94.7        | 80         |
| FSS (%TSS)    | 11.3              | 24.9        | 15.5        | 19.7       |
| VSS (%TSS)    | 88.7              | 75.1        | 84.4        | 80.3       |
| TSS (%)       | 10                | 29.7        | 5.28        | 20         |
| VSS/TSS (%)   | 88.7              | 75.1        | 84.4        | 80.3       |
| TKN (g N/L)   | 3.59              | 5.4         | 0.2         | 7.9        |
| NH₃-N (g N/L) | 0.98              | –           | 2.1         | –          |
| TP (g P/L)    | 34.57             | 1.8         | 2.3         | 1.7        |

aOFMSW

bMunicipal wastewater treatment plant primary sludge
For this investigation, different OFMSW treatment capacities were evaluated. However, emphasis is placed on the treatment of 200 MT of OFMSW, since it is of main interest to the working group. For the 200 MT capacity, 184,203 kg/day of digestate are obtained, which is mixed with 0.13 m³/day of polymer solution whose objective is the agglomeration of small particles to reach considerable sizes and form flocs, which are more easily eliminated. Digestate is treated in a sludge dryer with an evaporating capacity of 7500 kg/day, obtaining a mass flow rate of 5245 kg/day. Because this equipment requires high temperatures, water is evaporated at a temperature of 115 °C. Therefore, steam is used by a turbine with a capacity of 5100 kW, generating 108,927 kWh/day.

In CASE I, biogas generated in the digestor is directed at an absorption column (P-1) of carbon-steel, with a maximum column diameter of 52.5 m, a total specific area of 190 m²/m³ and a nominal diameter of 0.025 m. A removal is considered of NH₃, H₂S and mainly CO₂ at a diffusivity of 700 cm²/s in the gaseous phase and a superficial tension of 0.03 N/m. The biogas enters the absorption column at a mass flow of 17,309.4 kg/day (volumetric flow of 14,439.8 Nm³/day), with a molar composition of 47.30% methane, 49.02% carbon dioxide, 3.50% ammonia and 0.18% hydrogen sulfide. In this way, a biomethane stream of 4541.6 kg/day (6082.7 Nm³/day) is obtained, with a molar composition of 98.75% methane, 1.02% carbon dioxide, 0.22% ammonia and 0.01% hydrogen sulfide, removing 12,397.3 kg/day of carbon dioxide, 335.7 kg/day of ammonia and 34.8 kg/day of hydrogen sulfide are removed (about 97% of these components are removed). Therefore, a yield of 0.42 Nm³ biomethane/Nm³ biogas and a total yield of 30.41 Nm³ biomethane/MT OFMSW is achieved.

On the other hand, in CASE II biogas contained in the S-107 flow is treated with Fe₂O₃ utilizing the chemical reaction described in Techno-Economic Assessment section. In this reactor cooled water is used as transference agent at a speed of 210 kg/h at a 5 °C entry temperature and 10 °C exit. In the exit flow (S-109) a reduction is achieved from 0.74 kg/h (0.2% of the S-105 flow) to 0.007 kg/h (0.0021% in the S-109 flow). This last flow enters a tank which is fed 19,502 kg/day of water. The same amount is contemplated as coming out of the S-112 flow as steam at 257 °C and a pressure of 45 bar. Finally, a turbine is used to generate a total potency of 126,400 kWh/day for the process.

### Table 4 Size and price of the anaerobic digester at different amounts of OFMSW

| OFMSW (MT) | Size (m³) | Purchase cost (US $) | Units number |
|------------|-----------|----------------------|-------------|
| 100        | 2400      | 3,089,000            | 1           |
| 200        | 4750      | 4,782,000            | 1           |
| 300        | 3600      | 4,005,000            | 2           |
| 400        | 4750      | 4,782,000            | 2           |
| 500        | 5937      | 5,516,000            | 2           |

For this investigation, different OFMSW treatment capacities were evaluated. However, emphasis is placed on the treatment of 200 MT of OFMSW, since it is of main interest to the working group. For the 200 MT capacity, 184,203 kg/day of digestate are obtained, which is mixed with 0.13 m³/day of polymer solution whose objective is the agglomeration of small particles to reach considerable sizes and form flocs, which are more easily eliminated. Digestate is treated in a sludge dryer with an evaporating capacity of 7500 kg/day, obtaining a mass flow rate of 5245 kg/day. Because this equipment requires high temperatures, water is evaporated at a temperature of 115 °C. Therefore, steam is used by a turbine with a capacity of 5100 kW, generating 108,927 kWh/day.

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Steam is used as heat transfer agent in CASE I, with a demand of 262,685 kg/day, where 260,880 kg/day and 1808 kg/day are integrated into the digester (99.3%) and the sludge dryer (0.7%), respectively. In CASE II, freezing water is used in the piston flow reactor as heat transfer agent, requiring 5037 kg/day. Steam is the main agent in this case, utilizing 262,685 kg/day, where 260,878 kg/day (99.3%) are used in the sludge dryer and 1808 kg/day (0.7%) in the digester. The sludge dryer requires this agent to increase its temperature from 28.16 to 60 °C (5,433,855 kcal/h), while the digester necessitates changing from 25 to 35 °C (83,005 kcal/h). As in CASE I steam is the only agent, the totality of the steam is used in the sludge dryer (P-4), increasing its temperature from 26.6 to 60 °C (5,475,091 kcal/h).

There are usually losses of biogas in the digesters, particularly in the gas storage devices. In the downstream stages, an amount of biogas (methane and carbon dioxide) is also lost. It is difficult to know exact data, therefore, this loss is not considered in this research.

**Economic Profitability**

In ADP it is complicated to find profitability, since the costs generated by purchasing of equipment, materials, employees, among others are higher than the income price of electricity, tipping fee, biogas sale. However, the benefit of an ADP process involves costs of equipment purchase, discounted cash flow (DCF), working capital, and initial and validation costs. That is, for 200 MT in CASE I, equipment purchase costs are US $7,601,111; DFC of US $42,782,494; working capital of US $4064 and initial and validation costs of US $2,139,125. For CASE II, the purchase cost of the equipment is US $8,905,000; discounted cash flow of US $47,087,201; working capital of US $19,423 and initial and validation costs of US $2,354,360. Operating costs imply US $15,699/year for materials, US $1,283,475/year for dependent facilities and US $31,716/year for utilities in CASE I. For CASE II, the costs of materials are US $94,797/year, dependent on facilities of US $1,883,488/year and utilities of US $705/year.

In CASE I, revenue of US $1,225,525/year is obtained for the sale of biomethane, US $73,434/year for the sale of the digestate, and US $1,050,000/year for the discharge rate. In CASE I, a revenue can be obtained from the generation of electrical energy, if the steam generated in the sludge dryer (DLT-01 equipment) is used to generate electrical energy through a turbine, obtaining US $2,675,142/year, achieving a cumulative income of US $5,024,101/year. In CASE II, a total income of US $4,387,692/year is obtained, which is divided into a tip rate of US $1,050,000/year, sale of digestate of US $73,434/year and US $3,255,079/year of electric energy income. As such, the economic criteria used are not unfavorable in any of the case studies, because the investment and operation costs are higher than the amount of annual revenue, obtaining a negative NPV (US $18,915,067/year in the CASE I and US $28,636,890 in CASE II) which indicates that there is no economic feasibility in the process.

It is important to mention that in Mexico City there is a waste separation program by collectors and waste selection plants, therefore, ADP would only receive OFMSW. For this reason, the design of the process for this work does not consider a pretreatment. However, if the process design comes to consider shredding to condition the waste, the total investment could increase by 2.25% and 6.18% of the total income for CASE I. While for CASE II, the difference of the total investment would be 2.08% and 7.08% of total revenues. For both cases, shredding uses a high amount of energy during the process. Therefore, CASE II could be more affected because the main income comes from electric power.

A rapid test was performed using Fe2O3 in CASE I (in the same way as was used for CASE II), in order to purify the biogas from H2S before passing through the absorption tower. In this way, the efficiency of the absorption tower was corroborated, since very similar biogas purity values were

| Table 5 Profitability analysis of the proposed case studies (CASE I/CASE II) |
|-------------|------------------|------------------|------------------|
| MT          | Total capital investment (US$) | Annual operating cost (US$/year) | Total annual revenues (US$/year) |
| 100         | 28,085,306/30,709,648 | 818,098/1,375,648 | 2,512,972/2,194,899 |
| 200         | 44,925,683/49,460,984 | 1,330,890/2,129,755 | 5,024,101/4,387,692 |
| 300         | 70,344,231/76,489,279 | 2,057,095/3,211,084 | 7,538,338/6,584,125 |
| 400         | 88,096,595/93,667,410 | 2,611,643/3,940,020 | 10,047,900/8,778,658 |
| 500         | 95,888,059/108,178,630 | 2,857,837/4,555,025 | 12,559,793/10,973,269 |

(5,433,855 kcal/h).
obtained and especially on the economics criteria. Using Fe₂O₃, NPV of − US $ 19,440,499 was obtained, while using only the absorption tower NPV of − US$18,915,067 was achieved. In this way, it was decided to continue CASE I for this investigation, only with the absorption tower. For CASE II, it is necessary since it contributes to the purification of the biogas before combustion to obtain a lower emission of toxic gases to the environment.

**Sensitivity Analysis**

A sensitivity analysis is applied to find the influence of economic variables (such as raw material or product with added value) and have a better overview of the overall economy of the process. In this way, the analysis helps to understand the effect of the process variables, indicating which ones generate a significant change.

The sensitivity analysis was obtained by changing each input variable of the process model by a certain percentage, leaving the rest of the variables constant and quantifying the change in the process model at the output [59]. The prices of electricity, biomethane, OFMSW and digestate are variables considered for the study, as well as the quantity of OFMSW. In Fig. 3 the results for the NPV as main output for CASE I and CASE II are shown, where each variable is modified by ± 20 from its original value shown in Table 2. In both cases, the output response it stands out for the price of electricity, tipping fee, biomethane price, OFMSW quantity and digestate price, showing a greater effect on the NPV. However, for CASE I, tipping fee and biomethane show very similar effects to each other. While in CASE II a considerable effect is shown in the modification of the price of electricity, with respect to the other variables. Finally, the price of the digestate does not show a significant effect on the NPV for either of the two cases.

In order to find economic profitability in the anaerobic digestion process, operating as a biomethane or electric power generation plant, alternative income was sought such as the sale of the digestate, the integration of heat to process equipment and the income acquired by waste treatment. However, due to the high investment and operating costs and the current values of OFMSW and digestate treatment, there is a limitation on the feasibility of ADP. Often, these types of projects receive subsidies to find economic viability or to continue the study of some research project, such as a pilot plant. The design of these processes has benefited from the experience of these similar projects in Mexico and other countries.

Previously, it was mentioned that having NPV > 0 indicates reliability in the investment of a process. As part of this analysis, the amount of the subsidy required to find NPV = 0 was determined. At this point, there are no capital profits or losses, allowing the understanding of the economy of a process aimed at social benefit. There are different ways to support a project with a subsidy, e.g. “Environmental quality of electricity production, is a kWh subsidy paid to domestic producers of electricity from renewable sources and CHP who feed into the national grid” [60]. In Mexico, the project could be supported by a subsidy on the total investment, obtaining non-refundable financing from various institutions that make up the Development Banking in Mexico, which can finance to some extent this type of projects that contribute to waste treatment and sustainable energy generation.
Table 6 Subsidy based on OFMSW ability to achieve NPV = 0

| OFMSW (MT) | Subsidy by product | Total subsidy (US$) | Total inversion (US$) | Subsidy on total investment (%) |
|------------|--------------------|---------------------|----------------------|---------------------------------|
|            | Case I (US$/Nm³ of biomethane) | Case II (US$/kWh) | Case I | Case II | Case I | Case II | Case I | Case II |
| 100        | 2.845              | 0.135               | $2,205,143          | $2,768,714                       | $30,290,449          | $33,478,363          | 7.28   | 8.27   |
| 200        | 1.942              | 0.088               | $2,684,879          | $3,631,566                       | $47,610,562          | $53,092,551          | 5.64   | 6.84   |
| 300        | 2.068              | 0.093               | $4,479,417          | $5,737,406                       | $74,823,648          | $82,226,686          | 5.99   | 6.98   |
| 400        | 1.871              | 0.077               | $5,109,787          | $6,383,346                       | $93,206,382          | $118,452,884         | 5.48   | 5.39   |
| 500        | 1.964              | 0.064               | $6,804,912          | $6,650,409                       | $119,794,734         | $114,829,040         | 5.68   | 5.79   |

Table 6 shows the value of the subsidy required to find NPV = 0.

Biomethane production could compete with natural gas if the subsidies shown in Table 6 were available. On the other hand, a subsidy per unit of renewable energy can be considered, which depends on the technology and the size of the plant. Some authors like Zheng [61], report ¥ 0.25/kWh (~ US $0.038/kWh) using livestock and poultry waste as substrate. Verbeeck [62] mentions € 40 MW-h (~ US $0.049/kWh) and Gebrezgabher [60], a subsidy of € 0.097 kWh (~ US $0.117/kWh) using pig manure as substrate. On the total investment, Wang [63] mentions a subsidy of ¥ 522,500,000 (~ US $5,046,553) using waste from the agriculture and alcohol industry. Despite the fact that different reported substrates are handled, the subsidy is very similar in different regions of the world. With respect to technology, a greater subsidy is required in CASE I, and therefore a greater total investment. The total subsidy could be used in any of the case studies, since in general the percentage of the subsidy value for similar projects reaches 40% of the total investment. Thus, it is advisable to invest in the ADP process especially for CASE II.

Environmental Analysis

This analysis is based on the environmental impact categories described in Environmental analysis section. They are measured according to the impact indexes, which are divided into toxicological (HTPI, mg/kg; HTPE, mg/m³; TTP, mg/kg and ATP, mg/L) and atmospheric (GWP, kg CO₂ eq; ODP, kg CFC-11 eq; PCOP, kg C₂H₄ eq and AP, kg SO₂ eq). Toxicity is a relative term which reflects the potential of a chemical to do harm to biological tissue. No chemical is entirely safe nor entirely harmful since any chemical can come in contact with biological tissue without producing an effect on it, provided the concentration of the chemical is below a minimal effective level [64]. On the other hand, the measurement of the potential of greenhouse gas (GHG) emissions to the atmosphere is related to the atmospheric categories of environmental impact. There are chemicals that are more toxic than others and, hence some sort of quantitative measure of toxicity is required for the chemical products.

Table 7 Compounds and Environmental Impact Indices

| OFMSW (MT) | Main compounds (kg/year) | Environmental impact categories (Impact/year) |
|------------|--------------------------|---------------------------------------------|
|            | CO₂                      | H₂S                           | NH₃ | NaHCO₃ | Fe₂O₃ | SO₂ | HTPI   | HTPE   | TTP     | ATP     | GWP         | PCOP     | AP         |
| CASE I     |                          |                               |     |        |       |     |        |        |         |         |             |          |            |
| 100        | 2,147,621                | 5904                          | 56,932 | 15,876 | –     | –   | 62,510 | 494    | 62,510   | 44,221   | 524         | –          | 117,000    |
| 200        | 4,295,241                | 11,807                        | 113,865 | 31,752 | –     | –   | 124,830 | 988    | 124,830  | 88,441   | 1050        | –          | 234,000    |
| 300        | 6,442,862                | 17,710                        | 170,798 | 47,628 | –     | –   | 187,240 | 1480   | 187,240  | 132,662  | 1570        | –          | 350,900    |
| 400        | 8,590,482                | 23,614                        | 227,731 | 63,504 | –     | –   | 249,650 | 1978   | 249,650  | 176,903  | 2090        | –          | 467,900    |
| 500        | 10,738,000               | 29,517                        | 284,663 | 79,380 | –     | –   | 313,070 | 2465   | 313,070  | 221,104  | 2620        | –          | 584,900    |
| CASE II    |                          |                               |     |        |       |     |        |        |         |         |             |          |            |
| 100        | 2,219,695                | 210                           | 60,567 | 15,876 | 9576  | –   | 66,434 | 928    | 66,434   | 4892     | 541         | 3550       | 137,791    |
| 200        | 4,439,390                | 421                           | 121,134 | 31,752 | 192   | 49,313 | 132,837 | 1855   | 132,837  | 9784     | 1080        | 7110       | 274,583    |
| 300        | 6,659,084                | 631                           | 181,700 | 47,628 | 287   | 73,970 | 199,313 | 2775   | 199,313  | 14,685   | 1620        | 10,700     | 412,370    |
| 400        | 8,878,779                | 842                           | 8,878,779 | 63,504 | 383   | 98,626 | 265,747 | 3710   | 265,747  | 19,557   | 2160        | 14,200     | 550,170    |
| 500        | 11,098,470               | 314                           | 1006  | 79,380 | 1006  | 126,281 | 332,325 | 4714   | 332,325  | 19,295   | 2710        | 18,200     | 688,584    |
The indices of the categories are shown in Table 7, presenting each of the categories and their impacts generated per year, where only the Ozone Depletion Potential it was not shown in the results. This is because the emissions contain no chlorofluorocarbons or other halogen hydrocarbons, not damaging the ozone layer. Indexes of some categories are very similar in both case studies, especially in toxicological categories such as HTPI, HTPE and TTP. In the atmospheric categories, the difference is notable in the ATP category. Although low amounts are obtained, the amount of residual hydrogen sulfide causes the impact to be greater for CASE I. This can be treated with some extra equipment; however, the total investment would increase. This category is related to the maximum tolerable concentrations of different toxic substances in water by aquatic organisms [54].

GWP is one of the most important categories in the studies of environmental impact, because it is commonly used for impact studies regardless of the methodology to be used. It is a measure that mentions how much energy 1 MT gas emissions will absorb during a given period, relative to 1 MT CO2 emissions. The index for the GWP category is only slightly higher in CASE II. The higher the index, the more gases released warm the Earth [65]. CASE I does not present SO2 emissions, therefore it does not register an index in the PCOP category. This category is related to smog and degradation, due to the combustion of fossil fuels which generate other harmful substances. Also, SO2 is directly related to the AP category, although ammonia is the main causative compound for this category. For this reason, a similar impact is shown in the two case studies. The category is a consequence of the acids released into the atmosphere and subsequently deposited on land and water surfaces [54]. The PEI value on the toxicological categories is higher in CASE I and lower on the atmospheric categories. For example, when treating 200 MT of OFMSW, the value for PEI on the toxicological categories is 339,089 PEI/year and for atmospheric categories it is 235,050 PEI/year. While in CASE II, the categories indicate a PEI of 277,396 PEI/year on the toxicological categories and 282,773 PEI/year on the atmospheric categories.

Another way of knowing the impact generated by each of the processes is shown in Fig. 4, which shows the impact generated by the amount of OFMSW treated for the two cases, the impact by amount of biomethane produced and the impact by electricity generated. These results are presented for each of the OFMSW treatment quantities. The behavior is similar for the results shown in Table 7, however, it is notorious that for the production of 1 Nm3 of biomethane, the impact stands out for almost all categories.
Integrated Assessment

In this section, a simple procedure was established in order to comprehensively evaluate and compare the different process strategies. The criteria to integrate are the PB, used in this section to visualize the economy of the process in another way. Regarding the environmental criteria, total PEI was used, considering the toxicological and atmospheric categories, as a single result. The integration of both criteria gives a perspective that helps to make a decision on the type of ideal process design to contemplate a municipal ADP in Mexico. Figure 5 shows both criteria for different amounts of OFMSW. By increasing the amount of OFMSW, it can be observed that the PB criterion in both cases begins to have a similar behavior from 200 MT, despite its marked initial difference of 38.69% when treating 100 MT. Finally, at 500 MT, there is a minimum difference of 26.65%, obtaining a PB of 9.8 years and 16.8 years for CASE I and CASE II, respectively. For PB, the results are shown before taxes and without any subsidy. Previously, was mentioned that it is convenient to invest in a process when it is determined that PB is 4 years. However, those processes that have a public benefit, that are intended to contribute to the development of a state or country, PB can take longer and can usually be supported with some funding.

One way of summarizing the environmental impact in both cases is through PEI total. This criterion considers the indexes of every category, obtaining a total PEI value. Figure 4 presents different PEI capacities of the ADP in CASE I and CASE II. In general terms, environmental impact is lower in CASE II, although exit flows of the process involve a larger amount of chemical compounds. One close difference between both case studies for PEI values is around 2.35% at a capacity of 100 MT. When the quantity of OFMSW in the plant increases, the difference only increases a little, i.e., at 500 MT the difference between both case studies is 2.89%. The main interest towards this study is to find the economic feasibility of ADP, since it is the main impeding factor for which these types of technologies are not installed in the country. One of the importance of this process is that it is possible to combat the environmental impact generated with respect to landfills. In this way, in addition to obtaining profits, other problems generated by waste can be solved. It is convenient to select CASE I when demonstrating more favorable results with respect to CASE II in the economic evaluation, in addition to the fact that both case studies do not show significant difference in environmental impact.

Conclusions

An anaerobic digestion plant was evaluated for a case study in Mexico City using household OFMSW as substrate. For this purpose, the characterization of household OFMSW was carried out, obtaining their empirical chemical formula. The biogas yield is 72.2 Nm$^3$/MT OFMSW, which was used to perform an economic and
environmental analysis of the ADP, considering two case studies. CASE I contemplates biogas purification for sale as biomethane concentrated at 97% methane. CASE II uses steam and heat, generating electrical energy used within the same process and for sale. In particular, considering current investment and installation options, and low incomes, the results are not economically profitable, therefore a subsidy is required. According to sensitivity analysis, it was found that a subsidy on the total investment is required between 5.68 to 7.28% for CASE I and 5.79% to 8.27% for CASE II, depending on the amount of OFMSW. In the same way, it was found that the price of electricity, the amount of OFMSW and the tipping fee of OFMSW, are variables that have great influence on the NPV of the process and the price of biomethane for CASE I. On the other hand, the environmental impact was determined using the WAR methodology. The index in the toxicological and atmospheric categories is similar for the two case studies. There are some categories, such as AP in which there is a greater response for CASE I, influenced by hydrogen sulfide and ammonia. The integration of the economic and environmental criteria shows that when increasing the quantity of OFMSW, a very similar trend is found between the two case studies starting at 200 MT, where PB is 12.06 years for CASE I and 21.91 years for CASE II. The difference between both cases for PEI is only 2.89%, which indicates a very similar environmental impact. Therefore, it is convenient to select CASE I when demonstrating favorable economic results. This kind of study is very important to solve the problem of waste generation, especially for cities with a large number of inhabitants such as Mexico City. ADP profitability is subject to subsidies, however, only it requires a low percentage of the total investment. Because this study was carried out on a conceptual design of the process, future studies are recommended, considering the use of more technology on the process to achieve self-sustainability. In addition, an improvement in planning must be found so that this kind of project operates in different cities of the country, considering the function of the biogas plant in a circular economy context, integrating into reforms of energy supply and protection of the environment.

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of Interest All the authors declared that they have no conflict of interest.

References

1. Palacio, J.C.E., et al.: Municipal solid waste management and energy recovery. Energy Convers. (2019). https://doi.org/10.5772/interchopen.79235
2. Poniente, B., Plant, C., Inoculum, A., Nirmalkar, K., Murugesan, S., Garc, J.: Digest organic waste. Energies 12(12), 2343 (2019). https://doi.org/10.3390/en12122343
3. Cadena, C.E.M., Pérez, R.E.M.: Organic waste production in commercial and services economic units in Mexico City. Estud. Demogr. Urbanos Col. Mex. 33(3), 733–767 (2018). https://doi.org/10.24201/edu.v33i3.1804
4. Kiyasudeen, K., Ibrahim, S.M.H., Quaik, S., Ismail, S.A.: Prospects of Organic Waste Management and the Significance of Earthworms, pp. 23–44. Springer, New York (2016)
5. Lin, L., Shah, A., Keener, H., Li, Y.: Techno-economic analyses of solid-state anaerobic digestion and composting of yard trimmings. Waste Manag. 85, 405–416 (2019). https://doi.org/10.1016/j.wasman.2018.12.037
6. Choudhary, A., Kumar, A., Kumar, S.: Techno-economic analysis, kinetics, global warming potential comparison and optimization of a pilot-scale unheated semi-continuous anaerobic reactor in a hilly area: for north Indian hilly states. Renew. Energy 155, 1181–1190 (2020). https://doi.org/10.1016/j.renene.2020.04.034
7. Tian, H., et al.: Life cycle assessment of food waste to energy and resources: centralized and decentralized anaerobic digestion with different downstream biogas utilization. Renew. Sustain. Energy Rev. 150, 111489 (2021). https://doi.org/10.1016/j.rser.2021.111489
8. Tyagi, V.K., Fdez-Güelfo, L.A., Zhou, Y., Álvarez-Gallego, C.J., Garcia, L.I.R., Ng, W.J.: Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): progress and challenges. Renew. Sustain. Energy Rev. 93, 380–399 (2018). https://doi.org/10.1016/j.rser.2018.05.051
9. Vasco-Correa, J., Khanal, S., Manandhar, A., Shah, A.: Anaerobic digestion for bioenergy production: global status, environmental and techno-economic implications, and government policies. Bioresour. Technol. 247, 1015–1026 (2018). https://doi.org/10.1016/j.biortech.2017.09.004
10. Roychowdhury, P., Alghazo, J.M., Debnath, B., Chatterjee, S., Ouda, O.K.M.: Security Threat Analysis and Prevention Techniques in Electronic Waste. Springer, Singapore (2019)
11. Chen, J.L., Ortiz, R., Steele, T.W.J., Stuckey, D.C.: Toxicants inhibiting anaerobic digestion: a review. Biotechnol. Adv. 32(8), 1523–1534 (2014). https://doi.org/10.1016/j.biotechadv.2014.10.005
12. Campuzano, R., González-Martínez, S.: Characteristics of the organic fraction of municipal solid waste and methane production: a review. Waste Manag. 54, 3–12 (2016). https://doi.org/10.1016/j.wasman.2016.05.016
13. Fisgativa, H., Tremier, A., Dubert, P.: Characterizing the variability of food waste quality: a need for efficient valorisation through anaerobic digestion. Waste Manag. 50, 264–274 (2016). https://doi.org/10.1016/j.wasman.2016.01.041
14. Romo Millares, C.A., Medrano Vaca, C., Romero Tehuitzil, H., Arvizu Fernández, J.L., Huacuz Villamar, J., Beltrán Adán, J.: Generacion de electricidad mediante residuos solidos urbanos,
Unidad Electrif., p. 79. https://www.ineel.mx/docu/Guia-RSU.pdf?#page=20&zoom=auto,-99,466 (2012)

15. Murphy, J.D., Power, N.: Technical and economic analysis of biogas production in Ireland utilising three different crop rotations. Appl. Energy 86(1), 25–36 (2009). https://doi.org/10.1016/j.apenergy.2008.03.015

16. Montiel-Corona, V., Revah, S., Morales, M.: Hydrogen production by an enriched phototroph-trophic culture using dark fermentation effluent as substrate: effect of flushing method, bicarbonate addition, and outdoor-indoor conditions. Int. J. Hydrogen Energy 40(30), 9096–9105 (2015). https://doi.org/10.1016/j.ijhydene.2015.05.067

17. Chen, Y., Cheng, J.J., Creamer, K.S.: Inhibition of anaerobic digestion process: a review. Bioresour. Technol. 99(10), 4044–4064 (2008). https://doi.org/10.1016/j.biortech.2007.01.057

18. Behera, B.K., Varma, A., Behera, B.K., Varma, A.: Green Gaseous Fuel Technology. Springer, Cham (2019)

19. Ryckebosch, E., Drouillon, M., Vervaeren, H.: Techniques for transformation of biogas to biomethane. Biomass Bioenergy 35(5), 1633–1645 (2011). https://doi.org/10.1016/j.biombioe.2011.02.033

20. Escamilla García, P.E., Tavera Cortés, M.E., Sandoval Gómez, R.J., Salinas Callejas, E., Alvarado Raya, H.E.: Economic feasibility analysis for electrical generation from biogas in waste disposal sites in Mexico City. Appl. Econ. 48(59), 5761–5771 (2016). https://doi.org/10.1080/00036846.2016.1184378

21. Ali, G., Nitivattananon, V., Abbas, S., Sabir, M.: Green waste disposal of energy from waste via anaerobic digestion: a UK case study. Energy 44(1), 381–390 (2012). https://doi.org/10.1016/j.energy.2012.06.017

22. Carlsson, M., Naroznova, I., Moller, J., Scheutz, C., Lagerkvist, R.J., Salinas Callejas, E., Alvarado Raya, H.E.: Economic feasibility analysis for electrical generation from biogas in waste disposal sites in Mexico City. Appl. Econ. 48(59), 5761–5771 (2016). https://doi.org/10.1080/00036846.2016.1184378

23. Tsydenova, N., Morillas, A.V., Hernández, Á.M., Soria, D.R., Wilches, C., Belgica, A.: Feasibility and barriers for anaerobic digestion in Mexico City. Sustainability 11(15), 1–21 (2019). https://doi.org/10.3390/su11154114

24. Gutierrez, E.C., Xia, A., Murphy, J.D.: Can slurry biogas systems be cost effective without subsidy in Mexico? Renew. Energy 95, 22–30 (2016). https://doi.org/10.1016/j.renene.2016.03.096

25. Mwirigi, J., et al.: Socio-economic hurdles to widespread adoption of small-scale biogas digesters in Sub-Saharan Africa: a review. Biomass Bioenergy 70, 17–25 (2014). https://doi.org/10.1016/j.biombioe.2014.02.018

26. Vu, T.K.V., Vu, D.Q., Jensen, L.S., Sommer, S.G., Bruun, S.: Life cycle assessment of biogas production in small-scale household digesters in Vietnam. Asian-Australas. J. Anim. Sci. 25(5), 716–729 (2015). https://doi.org/10.5713/ajas.14.0683

27. Mezzullo, W.G., McManus, M.C., Hammond, G.P.: Life cycle assessment of a small-scale anaerobic digestion plant from cattle waste. Appl. Energy 102, 657–664 (2013). https://doi.org/10.1016/j.apenergy.2012.08.088

28. Roubik, D., Mazancová, J., Banout, J., Verner, V.: Addressing problems at small-scale biogas plants: a case study from central Vietnam. J. Clean. Prod. 112, 2784–2792 (2016). https://doi.org/10.1016/j.jclepro.2015.09.114

29. Spyridonidis, A., Vasiliadou, L.A., Akratsos, C.S., Stamatelatou, K.: Performance of a full-scale biogas plant operation in greece and its impact on the circular economy. Water (Switzerland) 12(11), 1–19 (2020). https://doi.org/10.3390/w12113074

30. Chotwattanasak, J., Puetpaiboon, U.: Full scale anaerobic digester for treating palm oil mill wastewater. J. Sustain. Energy Environ. 2(3), 133–136 (2013)

31. Ounde, P.O., Orhorhoro, E.K., Ebumi, P.O.B.: Design of three stages continuous anaerobic digestion (AD) Plant. Am. J. Eng. Res. 6(11), 311–321 (2017)

32. Rapport, J.L., Zhang, R., Williams, R.B., Jenkins, B.M.: Anaerobic digestion technologies for the treatment of municipal solid waste. Int. J. Environ. Waste Manag. 9(1–2), 100–122 (2012). https://doi.org/10.1504/IJEWWM.2012.044163

33. Challen-urban, J.M., Van Opstal, B., Parker, W.: Anaerobic digestion of the organic fraction of municipal solid waste (OFMSW): full scale vs laboratory results. J. Solid Waste Technol. Manag. 37(1), 33–39 (2011). https://doi.org/10.5276/JSWMT.2011.33
Anaya-Durand, A., Pedroza-Flores, H.: Scale-up: Escalamiento, el arte de la ingeniería química. Cienc. Ed. 23(1), 31–39 (2008)

Greenberg, A.E.: Advances in standard methods for the examination of water and wastewater. In: Proceedings of the AWWA Water Qual. Technol. Conf., pp. 11–13 (1984)

Yang, L., Xu, F., Ge, X., Li, Y.: Challenges and strategies for solid-state anaerobic digestion of lignocellulosic biomass. Renew. Sustain. Energy Rev. 44, 824–834 (2015). https://doi.org/10.1016/j.rser.2015.01.002

Ullah-Khan, I., et al.: Biogas as a renewable energy fuel: a review of biogas upgrading, utilisation and storage. Energy Convers. Manag. 150, 277–294 (2017). https://doi.org/10.1016/j.enconman.2017.08.035

Khan, M.U., et al.: Current status of biogas upgrading for direct biomethane use: a review. Renew. Sustain. Energy Rev. 149, 111343 (2021). https://doi.org/10.1016/j.rser.2021.111343

Cheng, J., Zhu, C., Zhu, J., Jing, X., Kong, F., Zhang, C.: Effects of waste rusted iron shavings on enhancing anaerobic digestion of food wastes and municipal sludge. J. Clean. Prod. 242, 118195 (2020). https://doi.org/10.1016/j.jclepro.2019.118195

Seider, W., Seader, J.D., Lewin, D.: Product and Process Design Principles. Synthesis, Analysis, and Evaluation, vol. 53. Wiley, New York (2003)

Zhao, X., Yao, G., Tyner, W.E.: Quantifying breakeven price distributions in stochastic techno-economic analysis. Appl. Energy 183, 318–326 (2016). https://doi.org/10.1016/j.apenergy.2016.08.184

La Rosa, A.D.: Life Cycle Assessment of Biopolymers. Elsevier, Amsterdam (2016)

Young, D., Scharp, R., Cabezas, H.: The waste reduction (WAR) algorithm: environmental impacts, energy consumption, and engineering economics. Waste Manag. 20, 605–615 (2000)

Hosseini Koupaei, E., Azizi, A., Bazyar Lakeh, A.A., Hafez, H., Elbeshbissy, E.: Comparison of liquid and dewatered digestate as inoculum for anaerobic digestion of organic solid wastes. Waste Manag. 87, 228–236 (2019). https://doi.org/10.1016/j.wasman.2019.02.014

Velmurugan, B., Ramanujam, R.A.: Kepadatan Penduduk Di Kabupaten Pemalang Tahun 2014. Int. J. Emerg. Sci. 1, 478–486 (2015)

Yang, G., Zhang, P., Zhang, G., Wang, Y., Yang, A.: Degradation properties of protein and carbohydrate during sludge anaerobic digestion. Bioresour. Technol. 192, 126–130 (2015). https://doi.org/10.1016/j.biortech.2015.05.076

Lopez-Arenas, T., González-Contreras, M., Anaya-Reza, O., Sales-Cruz, M.: Analysis of the fermentation strategy and its impact on the economics of the production process of PHB (polyhydroxybutyrate). Comput. Chem. Eng. 107, 140–150 (2017). https://doi.org/10.1016/j.compchemeng.2017.03.009

Gebrezagbher, S.A., Meuwissen, M.P.M., Prins, B.A.M., Lansink, A.G.J.M.O.: Economic analysis of anaerobic digestion: a case of Green power biogas plant in the Netherlands. NJAS Wageningen J. Life Sci. 57(2), 109–115 (2010). https://doi.org/10.1016/j.njas.2009.07.006

Zheng, L., et al.: What could China give to and take from other countries in terms of the development of the biogas industry? Sustainability 12(4), 1490 (2020). https://doi.org/10.3390/su12041490

Verbeeck, K., Buelens, L.C., Galvita, V.V., Marin, G.B., Van Geem, K.M., Rabaeys, K.: Upgrading the value of anaerobic digestion via chemical production from grid injected biomethane. Energy Environ. Sci. 11(7), 1788–1802 (2018). https://doi.org/10.1039/c8ee01059e

Wang, J., Chai, Y., Shao, Y., Qian, X.: Techno-economic Assessment of Biogas Project: a Longitudinal Case Study from Japan. Resour. Conserv. Recycl. 164, 105174 (2021). https://doi.org/10.1016/j.resconrec.2020.105174

Grossmann, I.E., Drabbant, R., Jain, R.K.: Incorporating toxicology in the synthesis of industrial chemical complexes. Chem. Eng. Commun. 17(1–6), 151–170 (1982). https://doi.org/10.1080/0098648208911622

EPA.GOV: “Understanding Global Warming Potentials | Greenhouse Gas (GHG) Emissions | US EPA,” Jan. 19, 2017. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials. Accessed 10 Aug 2020

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