Potential for energy use of food waste generated at the university restaurant of UNICAMP

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Abstract

The university restaurant (UR) of UNICAMP annually discharges, on average, 99 tons of food wastes, which are sent to landfills as a final disposal method. However, the biogas generated at this location has only been incinerated in flares, thereby wasting enormous potential for energy production. Besides, the distance between the university and the landfill has resulted in high transportation costs. Thus, anaerobic digestion (AD) systems stand out as an alternative to landfills, as they can be built in a decentralized manner on the property, in addition to being designed to optimize the production of biogas for self-generation of energy. Aiming at verifying the feasibility of implementing this process in the institution's facilities, food wastes from the UR were subjected to the biochemical methane potential (BMP) test. The results were used to design the AD system, which should have a volume of 24m³ and a height and diameter of 3m, with potential to generate approximately $6600m^3CH_4year^{-1}$. If converted to electricity, this would be enough to supply 7% of UR demand. If applied as cooking gas, they could replace 40% of the liquefied petroleum gas (LPG) used in the restaurant. The CH_4 could still be applied to supply 7% or 15% of the diesel needs of the boiler or campus buses, respectively. The process would also make possible to avoid transporting waste to the landfill, bringing savings of US$8163.98. Finally, to build the system, it would be necessary to invest between US$65921.08 and US$120741.89, with payback of 5 to 15 years.

Keywords: Food waste, Anaerobic digestion, Biogas, Bioenergy, Sustainability.

1. Introduction

Currently, the most used strategy for the treatment of food waste is landfills. However, with population growth, increased human consumption and the incorrect reception of waste, these areas have reached their maximum capacity in a short period. As a result, there are concerns about the lack of land to perform this technique in the long term, since landfills occupy large territories and when they reach their useful life, they must be closed and subjected to environmental recovery and monitoring processes. This is due to the decomposition of organic matter, which can cause infiltration of leachate, a liquid toxic to the soil and water bodies, and leaks of biogas, a gas mixture composed mainly of CH_4 and carbon dioxide (CO_2), greenhouse gases, in the atmosphere. In addition, as a result of the scarcity of territory, landfills are increasingly distancing themselves from waste generators, which has led to high transportation costs [7, 15, 9].

Landfills still have leaks of 20-60% of biogas and no capacity to recover the process effluent, the biodigested material. This has a high nutritional content and can be applied as a biofertilizer, being considered, in addition to biogas, another value-added product in the controlled processes of AD in reactors. Besides, most landfills only burn biogas captured in flares, thus wasting enormous potential for energy production. However, even though there is a large production of biogas in landfills, it occurs slower than in controlled environments (such as bioreactors) due to its size and lack of control, which allows the generation of energy only in the long term and in a finite way, since it has a limited useful lifetime [1, 6, 8].

With this, the biodigesters stand out as an alternative to landfills, as it promotes the decomposition of organic material in hermetically sealed environments, enabling the treatment of waste by reducing the organic load mediated by microorganisms, without escaping the products generated by the process. Also, this equipment can be installed in a decentralized manner, which allows the operation to be carried out in smaller dimensions and in specific locations. Thus, the project can be planned according to the particularities of the property, thereby increasing the system's performance. In addition to the control of process variables, which can be carried out effectively, and can also be automated, maximizing, in an optimized time, the production of value-added products supplied by the AD, such as biogas [10, 4, 5].

Biogas has been a highly valued product because, once most part of it consists of CH_4, it can act as an energy source for the generation of electricity, heat, biofuel and several other applications to replace fossil fuels. However, the energy use from biogas depends on the percentage of CH_4 in the gas mixture, which in turn varies according to the waste. Therefore, before the implementation of the process, experiments must be carried out to determine the CH_4 production capacity of the material, system efficiency and, consequently, the project's viability [2].

In this context, this study sought to determine the potential for energy use of food wastes generated by the UR of UNICAMP, through BMP tests. The economic feasibility analysis of the system for large scale was also carried out.

2. Methodology

2.1 Experimental analysis

The BMP tests followed the procedures described at VDI 4630 standard [14] procedures and took place in four main stages: i) collection and characterization of substrates, ii) pre-treatment of the substrate and preparation of the reactors, iii) inoculation and feeding of the systems and iv) incubation and monitoring of essays.

i) Collection and characterization: Food waste samples were collected in the UR of UNICAMP and the inoculum sludge was removed from the anaerobic mesophilic reactor for vinasse treatment at São Martinho plant in Iracemápolis – São Paulo. The materials were then subjected to verification of the hydrogen potential (pH) and to the test of the solid series, in triplicate, to determine their content of volatile solids (VS), according to the Standard Methods [3] number 4500-H^+ and 4540B and E, respectively, as shown in the Table 1.

Table 1. Characterization of substrate and inoculum

Sample	VS	pH
Food waste	261,9 g kg^{-1} ± 1,9	5,6
Inoculum	39,7 g L^{-1} ± 2,7	8,4

ii) Pre-treatment and preparation: Food waste was subjected to a maceration process through an industrial crusher, in order to reduce and homogenize the size of the particles, to facilitate the interaction between microorganisms and the substrate and improve the performance of the process in a wet way. With this, two duplicates were made: a) food wastes, following a 2:1 ratio of inoculum and substrate, whose quantitative distribution, as shown in Table 2, was determined through the SV of each material and the useful volume of the reactors and b) inoculum, as a negative control.

Table 2. Added amounts of substrate and inoculum in the reactors

Reactor	Substrate	Inoculum
Food waste + inoculum	21,29 g	278,85 mL
Inoculum	-	300 mL

iii) Inoculation and feeding: The substrate and inoculum were placed in 500 mL Duran flasks with 40% headspace. The pH of the mixture was then checked, adjusted with hydrochloric acid 1M to the appropriate range for the production of CH_4 (7.5) and the systems were subsequently sealed with a rubberized septum.

iv) Incubation and monitoring: The reactors were kept in a lab oven for a batch of 95 days at mesophilic conditions (30ºC), once the waste leaves the restaurant at room temperature and to reduce expenses with heating the system in case of scale gain. Periodically, the systems were manually shaken and submitted to quantification of biogas production with the aid of a manometer MAN 30 Amprose and a syringe S500 Hamilton Company, whose reading was normalized for volume under normal conditions of temperature and pressure (Equation 1). To determine the CH_4 content in the biogas, gas chromatography (U13 Construmaq) was used. The chromatograph operated with a thermal conductivity detector and a gas flow of 20 mL s^{-1}. The harsh gas used was hydrogen and the packed 80/100 mesh Heyesep D column was used, with a temperature maintained between 80 and 90ºC.

$$V = VM * \frac{(PM-PW)*TN}{PN*TS} \text{ (Equation 1)}$$

Where:
V = Volume of gas without water vapor (mL)
VM = Volume measured by the syringe (mL)
PM = Pressure measured by the manometer (kPa)
PW = Water vapor pressure in the TS (kPa), where TS (30ºC) = 4.3kPa
TN = Normal temperature (273K)
PN = Normal pressure (101,3 kPa)
TS = System’s temperature (K)

After the end of the experiment, it was possible to verify the behavior of the CH_4 production of food wastes over time, with the contribution of the inoculum (negative control) discounted, through the average of the BMP duplicates, calculated according to Equation 2.

$$BMP = \frac{Va}{VS_{added}} \text{ (Equation 2)}$$

Where:
BMP = Biochemical methane potential (NmLCH$_4$ gVS^{-1})
V_a = Accumulated volume of CH_4 (NmLCH$_4$)
VS_{added} = Volatile solids, reffering to the food wastes, added to the flask (gVS)

To estimate the operational parameters necessary for scaling the system and conducting energy and economic evaluations, such as HRT (hydraulic retention time), the modified Gompertz mathematical model was adjusted to the experimental curve of the BMP of food wastes, using Equation 3 with aid of the Excel Solver tool.

$$Va(t) = Vf * \exp(-\exp(\frac{Vd}{Vf} * e^1 * (\lambda - t) + 1)) \text{ (Equation 3)}$$

Where:
Va(t) = Volume of CH_4 accumulated as a function of time (t) (NmLCH$_4$ gVS^{-1})
Vf = Final volume of CH_4 accumulated (NmLCH$_4$ gVS^{-1})
Vd = Maximum daily volume of CH_4 at time (t) (NmLCH$_4$ gVSday^{-1})
λ = Lag phase time (days)
t = Observation time (days)

To verify the efficiency of the experimental test, it is possible to calculate the biodegradability obtained in the system, through the BMP ratio and the theoretical biochemical potential of methane (TBMP), which can be found through Equation 4, where the percentages of organic fractions were estimated by the UR menu on the day of sample collection (Table 3).

$$TBMP\ (NmLCH_4\ gSV^{-1}) = 415 * (\%Carbohydrate) + 496 * (\%Protein) + 1014 * (\%Lipid) \text{ (Equation 4)}$$

Table 3. Nutritional composition of the UR menu

Menu	Carbohydrates (g)	Proteins (g)	Lipids (g)
Rice	29.4	2.6	4.4
Bean	10.8	3.8	2.5
Beet salad	7.7	1.4	0.2
Swine palette	1.5	19.9	2.3
Braised cabbage	2.5	0.6	0.1
Orange	7.1	0.8	0.1
Bread	11.7	1.6	0.3

2.2 Potential for energy use

As the UR menu changes daily, naturally the content of organic matter in the waste will also vary, which will impact on the production of biogas. Thinking about it and considering that the system's proposal is to operate in a semi-continuous way, that is, fed once a day, a temporal analysis of the solid content of the food wastes was carried out for 1 month, to incorporate the fluctuation of the characteristics of the waste in energy calculations and thus determine pessimistic and optimistic scenarios for the volume of biogas produced and for each suggested application for gas within the university.

With the BMP curve, the kinetic parameters and the variation of food waste volatile solids over time, it was possible to estimate a range of gas volume to be generated annually at the university, as shown by Equation 5.

$$PCH_4 = BMP(HRT) * VS_{fw} * P_{fw} * \frac{1}{1000} \text{ (Equation 5)}$$

Where:
PCH_4 = CH_4 production (m^3 $year^{-1}$)
BMP(HRT) = Biochemical methane potential on the given day ($NmLCH_4$ gSV^{-1})
HRT = $\frac{Vf}{Vd}$ (days)
VS_{fw} = Volatile solids from UR food waste (g kg^{-1})
P_{fw} = Annual UR food waste production (kg)

Thus, with the maximum and minimum CH_4 production scenarios found, it was possible to establish a range of annual electricity generation potential (Equation 6), replacement of diesel in the internal buses or in the boiler (Equation 7), which assists heating processes in the UR, and LPG (Equation 8), which acts as cooking gas in the university's smallest restaurant.

$$E = P_{CH4} * LCP_{CH4} * \eta ICE * \frac{1}{3,6} \text{ (Equation 6)}$$

Where:
E = Electricity (MWh $year^{-1}$)
LCP_{CH4} = Lower calorific power of CH_4 (35,8 MJ m^{-3})
ηICE = Electric performance of biogas internal combustion engine (25%)

$$Vdiesel = P_{CH4} * \frac{LCP_{CH4}}{LCP_{diesel}} \text{ (Equation 7)}$$

Where:
Vdiesel = Volume of diesel replaced (L ano^{-1})
LCP_{diesel} = Lower calorific power of diesel (36,6 MJ L^{-1})

$$Q_{GLP} = P_{CH4} * \frac{LCP_{CH4}}{LCP_{LPG}} \text{ (Equation 8)}$$

Where:
Q_{LPG} = Amount of replaced LPG (kg ano^{-1})
LCP_{LPG} = Lower calorific power of LPG (46,4 MJ kg^{-1})

2.3 System sizing and planning

To achieve economic viability, it was necessary to estimate an initial investment for the idealization of the AD system. For that, it was necessary to choose some operational parameters: the plant can operate with semi-continuous feeding, under mesophilic conditions, with 1 stage, humidifying by the recirculation of the liquid phase of the biodigested material. Also, it can employ strategies for crushing the residue mechanically and agitating by internal recirculation of material, as shown in Figure 1. The same was done for each suggested application of biogas within the campus.

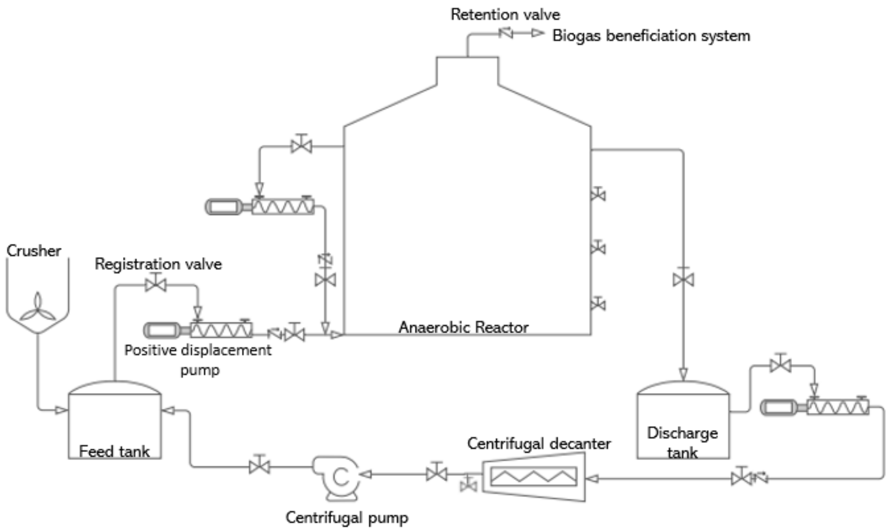

Fig. 1 Scheme of the AD system for UR food waste (Author, 2020)

After choosing the specifications of operation, it was possible to dimension the anaerobic reactor, considering the maximum amount of waste generation in the UR (500 kg day^{-1}), as well as the highest TS (total solids) content found in this substrate, determined by temporal analysis, so that the volume of the digester is not underestimated. Regarding to the TS content in the substrate, a dilution of the material up to 15% ST was considered. Therefore, to find the volume of liquid phase to be added in the feed, Equation 9 and Equation 10 were used.

$$TSi * Vi = TSf * Vf \text{ (Equation 9)}$$
$$Vl = Vf - Vi \text{ (Equation 10)}$$

Where:
TSi = Initial total solids (kg)
Vi = Initial volume (L)
TSf = Final total solids (kg)
Vf = Final volume (L)
Vl = Liquid phase volume (L)

From the amount of waste and liquid phase to be added per day to the feed and the system's HRT, the useful volume of the reactor was found, through Equation 11.

$$V = Q * HRT \text{ (Equation 11)}$$

Where:
V = Reactor useful volume (m^3)
Q = Daily feed flow (m^3 dia^{-1})

It is also recommended to add 10% more volume in the reactor as a safety measure, thus composing the gross volume. Thus, with the volume, it was possible to find the internal diameter (Di) and the height of the reactor (H), through Equation 12 and Equation 13 and 14, which show the range of optimum relationship between Di and H for biodigesters, reported by [12].

$$Vb = \pi * Di^2 * H \text{ (Equation 12)}$$

$$0,6 \leq \frac{Di}{H} \leq 1 \text{ (Equation 13)}$$

$$3,0m < H < 6,0m \text{ (Equation 14)}$$

Where:
Vb = Gross volume (m^3)
Di = Internal diameter (m)
H = Height (m)

2.4 Economic feasibility analysis

2.4.1 Revenues and costs

After quantifying all possible products to be replaced by CH_4, it was verified the savings that each application would bring to UNICAMP and the costs avoided by not disposing of waste in landfills, according to the information set out in Table 4.

Table 4. Annual consumption and expenditure on energy and waste disposal at UNICAMP

Application	Consumption	Invoice (US$)
Electricity[1]	253 MWh	15729.50
Vehicle fuel [2]	223916 km or 44783 L diesel	25192.54[4]
Cooking gas[3]	13000 kg LPG	11928.87[5]
Boiler fuel[1]	88000 L diesel	49503.85[4]
Final disposal at the landfill	99 tons	1746.32
Waste transport		3734.23
Waste storage		2679.75

[1]UR, [2]UNICAMP internal buses, [3]UNICAMP's smallest restaurant, [4]Based on the price of diesel in August 2020 in Campinas, [5]Based on the price of LPG in August 2020 in Campinas.

In addition to the savings, it was also necessary to find the annual costs to keep the plant in operation, which in this study was considered as expenses with maintenance and repairs (1% of the initial investment [13]) and electricity (sum of the electrical consumption of the equipments in the plant according to its power and hours worked). Thus, subtracting the annual costs from the savings generated for each application, it was possible to verify the range of revenue to be brought by the system.

It is worth mentioning that the data referring to waste generation, CH_4 production, consumption and energy bills were calculated according to the period of operation of the university activities analyzed, where 1 month corresponds to 20 days and 1 year equals 11 months of 20 days each. There is operation throughout the year, but all vacation and holidays are equivalent to 1 conventional month.

2.4.2 Investments and feasibility indicators

After the systems planning was carried out, it was possible to gather all information about the equipments, devices and services necessary for the construction of the AD plant at UNICAMP. Thus, through market research and contact with suppliers, a budget estimate was made for each suggested system.

With the revenues and the initial investment, it was possible to determine the viability of each application for a 20-year horizon, with the aid of simple and discounted paybacks (Equation 15 and 16), net present value (Equation 17) and internal rate of return (Equation 18).

$$PB_{simple} = \frac{Io}{R} \text{ (Equation 15)}$$

Where:
PBsimple = Simple payback (years)
Io = Initial investment (US$)
R = Revenue (US$)

$$PBdiscounted = \sum_{t=1}^{n} \frac{CFt}{(1+MAR)^t} \text{ (Equation 16)}$$

Where:
CF = Flow cash (US$)
MAR = Minimum attractiveness rate (%)
t = Period corresponding to cash flow (year)
n = Project life time (years)

$$NPL = \sum_{t=1}^{n} \frac{CFt-Io}{(1+MAR)^t} \text{ (Equation 17)}$$

Where:
NPL = Net present value (US$)

$$IRR = 0 = \sum_{t=0}^{n} \frac{CFt-Io}{(1+MAR)^t} \text{ (Equation 18)}$$

Where:
IRR = Internal rate return (%)

In this study, the current basic interest rate of the Brazilian economy was considered as MAR (Selic = 2.31% per year).

3. Results and discussion

With the BMP assay and its adjusted curve (Figure 2), the kinetic parameters Vf (406.7NmLCH_4 gSV^{-1}) and Vd (13.9NmLCH_4 $gSVdia^{-1}$) were determined, which made possible to approximate their ratio to HRT for calculation purposes, since the data generated by the Gompertz model obtained a R^2 greater than 99% in relation to the experimental data. Besides, the biodegradability obtained in the system resulted in 92%, since BMP = 416.2 ± 13.9 NmLCH4 gSV^{-1} and TBMP = 450.5 NmLCH_4 gSV^{-1}, which indicates that the tested system came very close to 100 % removal of organic load, which indicates that the maximum potential may have been reached, since part of the material is used for microbial development, making total process efficiency not possible.

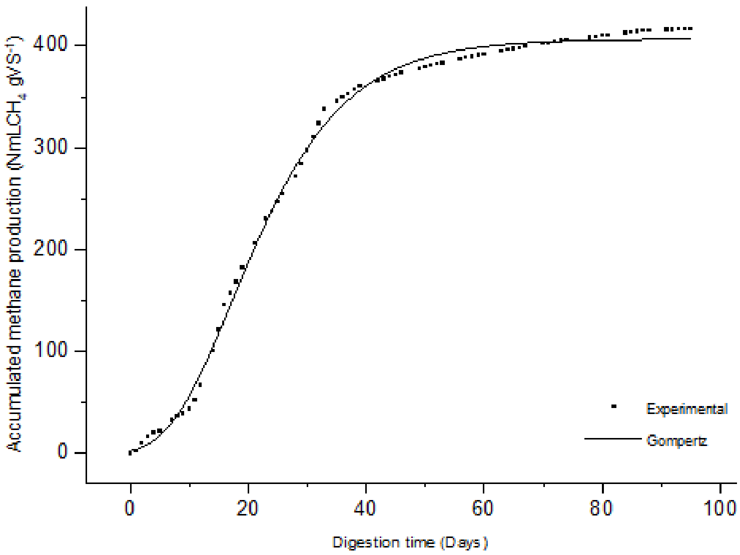

Fig. 2 BMP of food waste and modified Gompertz curve adjustment to the experimental data (Author 2020)

With the BMP at the determined HRT (297.2NmLCH_4 gSV^{-1}) and the temporal analysis of the VS content found in the food waste (Figure 3), it was possible to estimate the range of annual CH_4 production that could be generated at UNICAMP (5582Nm³CH_4 to 7707Nm³CH_4).

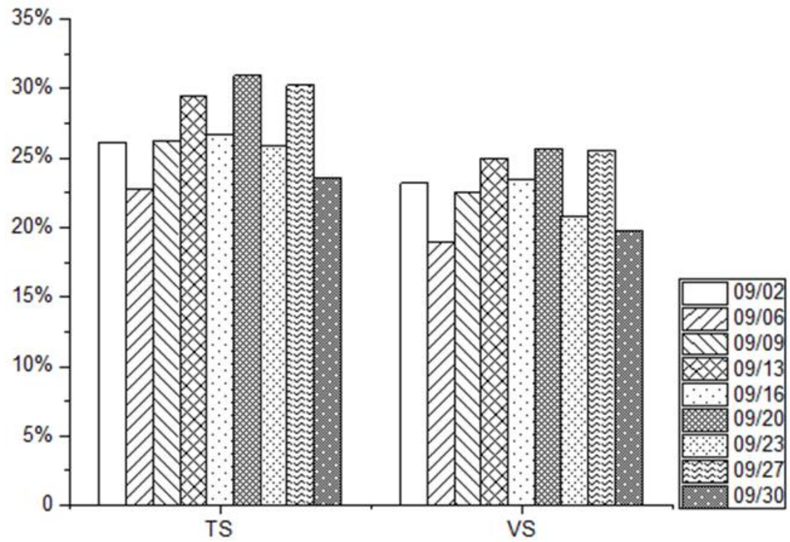

Fig. 3 Variation in the solids content of food waste over time (Author, 2020)

With that, the minimum and maximum scenarios of replaced quantities and savings generated for each suggested application of CH_4 within the University were determined, as can be seen in Table 5 and Table 6.

Table 5. Quantity range of products to be replaced by CH_4

Application	Minimum	Maximum
Electricity	14 MWh	19 MWh
Vehicular and boiler fuel	5473 L diesel	7556 L diesel
Cooking gas	4307 kg LPG	5946 kg LPG

It can be said that the CH_4 production range to be generated by UNICAMP has the potential to electrically supply 10 to 14 residences in Campinas every day, considering that according to the Government of São Paulo, each household consumes 6.4kWh dia^{-1} [11]. The quantity of diesel to be replaced by CH_4 may be sufficient to keep an urban bus in operation for 141 km to 195 km per day, considering that according to ABIOGÁS, 1 L of diesel is equivalent to 5 km driven [1]. The amount of LPG, on the other hand, has the potential to replace 2 canisters of kitchen gas of 13 kg per day

Table 6. Annual savings generated by CH_4 replacement (US$)

Application	Minimum	Maximum
Electricity	870.27	1201.43
Vehicular and boiler fuel	3102.08	4282.69
Cooking gas	3982.24	5497.89
Waste disposal	8163.98	

In terms of the demands of university, the electric energy produced from CH_4 could supply 5 to 8% of the electricity demand in the UR. The amount of diesel that could be replaced by biomethane as a vehicle fuel would be enough to fully supply the internal nocturnal circular bus, which runs 104.5 km day^{-1}, making 11 trips daily. In terms of total fleet, the gas could supply 12 to 17% of the diesel demand in UNICAMP's internal circulars buses. Regarding to diesel applied in the UR boiler, the use of biomethane could supply 6 to 9% of the fuel demand used to generate steam in the kitchen. Finally, cooking gas showed the highest percentage of replacement among all possible applications within UNICAMP, being able to supply 33 to 46% of the LPG demand of the institution's smallest restaurant. It is worth mentioning that, regardless of the chosen application, all scenarios will have the addition of savings generated by not directing waste to the landfill, which may even bring the largest savings among all situations.

As for the dimensioning of the DA system, verifying the temporal analysis of the solids content, it was possible to find the highest TS content (31%), with the conclusion that for the aforementioned results to be achieved, the university would have to build an anaerobic reactor with 23.6 m^3 of gross volume and 3 m in height and diameter. Knowing the size of the plant, it was possible to choose the best location within the campus to build the project. The decision was based on allowable safety distances and proximity to the UR.

The investment estimate for building the system can be seen in Table 7. The same was done for all the suggested applications: electricity (US$69136.45), vehicular fuel (US$120741.89), boiler fuel (US$65921.08) and cooking gas (US$77938.80). There are differences in investments due to the specificities of each scenario. However, the costs of the AD system, control devices, security, measurement, storage and displacement of gas do not change for every scenario.

Table 7. Simplified investment for the idealization of the AD plant

Equipments	**Specificity**	**Units**	**Price (US$)**
Crusher	Industrial stainless steel	1	1560.93
Feed tank	HDP[1] 1m^3	1	194.00
Pump	Progressive cavity	3	2753.80
Anaerobic reactor	GRP[2] 23,6m^3	1	8300.05
Discharge tank	HDP 1m^3	1	194.00
Decanter	Centrifugal	1	17458.38
Pump	Centrifuge	1	133.12
Pipe material	HDP 150mm	29m	154.03
Valve	Guillotine HDP	7	459.45
Valve	Retention HDP	3	97.38
Valve	Register PC[3]	6	19.82
Accessories	-	-	882.63
Total			**34839.30**

[1]High density polyethylene; [2]Glass-reinforced plastic; [3]Polyvinyl chloride

The electricity and boiler fuel scenarios showed the lowest investments. In the first case, there are higher expenses in relation to the acquisition of the motor-generator; in the second, the highest costs were for adapting the boiler to diesel-gas and for building a small pipeline to direct CH_4 from the AD plant site to the boiler. The application of biogas as cooking gas presents an intermediate investment compared to the other scenarios, due to the greater distance from the plant site to the university's smaller restaurant, which increases the size of the gas pipeline and consequently the investment. The application of CH_4 as a vehicle fuel presents the largest investment, due to the gas treatment system, which must carry out, in addition to the removal of moisture and hydrogen sulfide, the removal of CO_2, transforming it into biomethane (> 95% CH_4 in the biogas). Furthermore, there is the need for adapting the bus to diesel-gas and for high-power compressors to store fuel in cylinders at 200bar.

The economic indicators for each application can be viewed in Table 8, knowing that the annual cost of each scenario resulted in: electricity (US$1264.21), vehicular fuel (US$2821.27), boiler fuel (US$1431.96) and cooking gas (US$1552.14).

Table 8. Economic viability of the pessimistic and optimistic scenarios of the suggested applications

Application	Simple payback (years)	Discounted Payback (Years)	NPL (US$)	IRR (%)
Electricity	7.9-8.3	8.9-9.3	64274.11-69994.01	10.5-11.1
Vehicular fuel	11.3-12.8	13.2-15.3	29479.02-49750.50	4.7-6.2
Boiler fuel	5.4-6.1	5.8-6.6	109341.96-129965.29	15.5-17.7
Cooking gas	5.8-6.7	6.3-7.3	110757.73-137232.47	13.9-16.3

Although the paybacks are relatively high, all scenarios are financially viable, since NPL resulted in a positive value and IRR resulted in a higher rate than MAR. The applications of biogas as a boiler fuel and as a substitute for LPG are presented as the most viable alternatives once they presented greater savings. The electric energy scenario does not show a similar economy due to the smaller size of the plant, which makes it less attractive financially, even though it does not have the challenge of building a pipeline. Finally, the application as a vehicle fuel is shown to be the least viable, due to the need for high investments as a result of the low diffusion of biomethane in Brazil, which makes technologies related to the use of fuel in small plants more expensive.

4. Conclusions

With the construction of the AD system, the university would avoid the final disposal and transport of its waste to landfills. It could also supply internal demands with the energy generated by the process, which would help to reduce the use of fossil fuels and overcrowding of landfills. Besides, the system would favor environmental conservation and the diversification and security of the energy matrix. In addition, the project has the potential to become a technology for training, research and academic teaching in the area of waste treatment and bioenergy. Thus, it can contribute to sustainable development and the concept of the university as a living laboratory, carrying out the environmentally appropriate treatment of organic wastes and generating clean energy on campus.

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