Evaluation of the environmental, technical and economic performance of anaerobic co-digestion processes in Colombian scenarios

A. Espejo[1], P. Torres[1], J. Mosquera[1], C. Rangel[2], I. Cabeza[1,3], N. Ortiz[1], P. Becerra[1], P. Acevedo[1,4]

[1] Department of Environmental Engineering, Universidad Santo Tomás, Bogotá, Carrera 9 No. 51 - 11, Colombia
[2]Departament of Engineering Process, Universidad EAN, Bogotá, Carrera 11 No. 78 – 47, Colombia
[3]Engineering Department, Politécnico Grancolombiano, Bogotá, Calle 57 No. 3 – 00 Este, Colombia
[4]Department of Industrial Engineering, Universidad Cooperativa de Colombia, Bogotá, Avenida Caracas 37 - 63, Colombia

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Presenting author email: paola.acevedop@ucc.edu.co

Abstract

The present work evaluates the technical, environmental and economic performance of the anaerobic co-digestion process as an alternative for the sustainable and efficient valorization of residual biomass from agro-industrial activities in Colombia. Three (3) different substrate mixtures were assessed, with the following methodology stages:

1. The treatment capacity was defined by using the available information. After this, all the mass and energy balances were constructed for each substrate mixture.
2. The environmental performance was evaluated through the quantification of the potential environmental impacts employing the Life Cycle Assessment (LCA) technique using the *SimaPro* software, where the behavior of the different mixtures was evidenced.
3. An economic evaluation was carried out, taking into account the operating and administrative costs, incomes, profits and depreciation of the equipment.
4. Finally, the best mixture was chosen by the methodology of the analytic hierarchy process.

The results obtained show that the best mixture to generate electric energy is mixture three since it generates the most significant amount of biogas at 56401.248 m^3 per year. The LCA analysis confirms that the mixture three had the best environmental performance in almost all the categories evaluated. Besides, this mixture obtained the best results in the economic study with an NPV for the last year of COP 5,507,646,009 and an IRR of 38.99%.

Introduction

Colombian economic development has increased the amount of solid waste, derived from different productive sectors. There are significant environmental problems from residue management, which can be mitigated through various technologies available for the industries. The organic biomass in the country has excellent potential for the implementation of biological processes for energy generation and the implementation of technological schemes of use [1]. The anaerobic digestion is one of the most studied processes, but there are only a few researches over the technical, environmental and economical approach of the implementation of this technology in the Colombian industry.

Several varieties of residues derivate from agro-industrial activities in Colombia are susceptible to be valorized, some of them are pig manure (PM), sewage sludge (SS), organic fraction of municipal solid waste (OFMSW), residues from the bottled fruit drinks industry (RBFDI) and cocoa industry residue (CIR) [2]. The individual biomethanation potential of these residues was evaluated by Cabeza et al [3], proving the potential for the implementation of AD technologies. Also, Mosquera et al [4], approached the biochemical potential of methane (BPM) and synergies of different mixtures of these substrates, through the evaluation of control variables of ACoD process, which benefits the profits that could be optioned if this technology is implemented. In fact, electric energy production, capitalization of digestato, to get profits from the high content of phosphate, nitrogen, other macro-nutrients and trace elements essential for plant growth; and the reduction of pollution show that ACoD is sustainable and has a significant advantage over other biological treatments [5].

In terms of the electric energy production from biogas, in 2016 Europe leads with 207.245Gwh follow by Asia 152.315 GWh, North America 97.800Gwh, Latin America 72.727 GWh, Commonwealth of Independent State 4.019 GWh and middle east 121 GWh [6]. Then, most biogas production occurs in developed countries with large-scale systems, while small-scale systems have been implemented in developing countries from Asia, Africa, and Latin America, so this technology will be feasible at any scales, and its feasibility is related to the methane potential of the substrates [7, 8]. Nevertheless, there is a high capital cost of an AD facility, the required infrastructure and associated labor cost, which need to be evaluated along with the process control and monitoring of established control variables (VFs, alkalinity, temperature, OLR levels) to avoid inhibition. From an economic feasibility assessment, the net present value will give decision makers an estimated value of the aerobic co-digestion system investment according to the estimate methane production [9, 10].

The estimation of the potential environmental impacts, of waste to energy technologies, has been highly studied through life cycle assessment methodology. Previous studies of the environmental performance of the anaerobic digestion considered, as maximum outputs are electricity (84%), heat (37%), fuel (27%) and valuable materials (77%) [11]. In addition, it is the preferable option for biomass substrates, even though within the tech-economical aspect for biogas plants in developed countries are not found to be as feasible as incineration plants. Garfí et al [12], performed an LCA of anaerobic digestion in the Colombian context, by the evaluation of different scenarios for the implementation of low-cost digesters in small-scale farms, proving its implementation as an alternative for the improvement of standard living of rural families.

Consequently, this research evaluates the technical, environmental and economic performance of the anaerobic co-digestion process as an alternative for the sustainable and efficient valorisation of residual biomass from agro-industrial activities in Colombia. The aim was accomplish by: the proposal of three large-scale systems, considering three substrate mixtures of organic solid wastes available in Cundinamarca (department) [2, 4]; using a LCA methodology to assess the environmental performance of each mixture, from the waste management to the electric energy production; and an economic evaluation, addressed in order to define the feasibility of this technology. The compressive analysis of this research could generate a business opportunity for Colombian industries, located in the Andean region; based on the economic profitability and environmental benefits of the implementation of this technology.

Material and Methods

Technical framework

The residual biomass from agro-industrial activities in the department of Cundinamarca has been previously studied; searching for their valorisation through second-generation biofuels production. Mosquera et al [4] Evaluated the anaerobic co-digestion of pig manure (PM), sewage sludge (SS), organic fraction of municipal solid waste (OFMSW), residues from the bottled fruit drinks industry (RBFDI) and cocoa industry residue (CIR), for the maximization of the biogas production of different mixtures. The maximized mixtures (see Table 1.) were chosen for this study using the biogas production projections and the availability of the substrates reported.

Table 1. Maximized mixtures.

	PM (%)	**CIR (%)**	**SS (%)**	**RBFDI (%)**	**OFMSW (%)**
Mixture 1			8.321	68.452	23.227
Mixture 2	28.297	35.336		36.367	
Mixture 3		14.550	29.612		55.838

The residue availability reported by Piñeros et al [2], show that the residues are highly accessible in different municipalities of Cundinamarca, the cocoa industry is placed in Yacopí, piggery farms in San Antonio de Tequendama, sewage sludge from Madrid wastewater treatment plant, fruit juice industries are in Bogotá as well as the OFMSW recovery. In this way, the market research reported allows the construction of mass and energy balances by the definition of the production systems, and the corresponding unit processes for the three co-digestion plants. As follows, the first step was the calculation of limiting substrate and the definition of installed capacity. The installed capacity was determined by the annual residue availability amount, the composition of each mixture, and an average operation capability of 80%.

The following step was the reactors sizing and biogas production projection, considering a batch process with a hydraulic retention time of 21 days, a total operation time of 345 days yearly for a total of 16 cycles per year. This process engages the following equations.

$$Substrate\ volume\ (m^3) = \sum \frac{Density\left(\frac{Ton}{m^3}\right)}{Mass\ (Ton)} \qquad (1)$$

$$Reactor\ water\ percentage\ (40\%) = (Substrate\ volume\ (m^3) * 0{,}4) \qquad (2)$$

$$Air\ percentage\ in\ the\ reactor\ (20\%) = (substrate\ volume\ (m^3) * 0{,}2) \qquad (3)$$

$$Reactor\ volume = \ (Substrate\ volume\ (m^3) + Reactor\ water\ percentage\ (m^3) + Reactor\ air\ percentage\ (m^3)\ ) \qquad (4)$$

For the determination of energy production was assumed that only 65% of the biogas is suitable for electric energy production (the remaining 35% is used for self-warming), and the 0.35 refers to the efficiency of the generator engine.

$$CH_4\ Production\ per\ cycle(m^3) = \left(BMP \left(\frac{m^3 CH_4}{Ton\ SV}\right)\right) * \sum Tons\ of\ VS\ in\ the\ mixture \qquad (5)$$

$$Energy(Kwh) = (CH_4\ Production\ per\ cycle(m^3)\ * Biogas\ energy\left(\frac{kWh}{m^3}\right) * 0{,}65 * 0{,}35 \quad (6)$$

Life cycle assessment

In order to assess the environmental impact of biomass to energy pathways, a life cycle assessment (LCA) was performed. LCA is a comprehensive, systematic and standardized methodology for the quantification of the total environmental impacts of a product, process or activity; it involves the evaluation of environmental aspects in a cradle-to-grave approach. Evaluation of the environmental impacts results from the identification and quantification of the inputs of materials and energy, and the outputs primary emissions to air, water and land through the products life cycle [13]. An LCA is normally executed in four phases; goal and scope definition, inventory analysis, impacts assessment and results interpretation.

The goal of the LCA is to estimate the individual environmental impact of energy production from three different residual biomass mixtures. The LCA performed had a “gate-to-gate” approach, starting with the transport of the raw materials and ending with electric energy production. After the definition of the technical aspects of each plant, unit processes are described through a literature review, including equipment data sheets.

Reference data for the inventory analysis corresponds to one production cycle. Three functional units (FU) were taken into account for the quantifications of the environmental impact, Tons for the treated waste and water consumption, kWh for energy consumption and cubic meters (m^3) for the biogas production.

The potential environmental impact was estimated using the software *SimaPro 8,* an analytical tool following the ISO 14040 standards . The environmental product declaration (EPD) methodology allowed the impact categories definition, it is a method employed for the assessment of renewable energy projects, where each environmental factor is associated with the correspondent category, allowing the quantification and representativeness of the environmental impacts expressing the results in specific equivalent units [14]. Table 2.

Table 2. Potential environmental impacts categories according to the EPD methodology.

Potential impact categories	***Equivalent units***
Terrestrial acidification	Kg SO_2 eq
Freshwater eutrophication	Kg PO_4 eq
Climate change	Kg CO_2 eq
Photochemical oxidation	Kg C_2H_4 eq
Ozone depletion	Kg CFC-11 eq
Abiotic depletion	Kg Sb eq

The interpretation of the results was accomplished by the generation of three environmental profiles, one for each mixture or scenario; the profiles allow the quantification of the influence of each unitary processes proposed over each impact category.

Economic assessment

In order to carry out the economic assessment, projected utilities for the next ten years were taken into account, for which the following analyses were made for each mixture: i) Evaluation and quotation of basic equipment, auxiliary equipment, and services necessary for each plant. The prices of each of the equipment and components of the plant were consulted on the web. ii) Definition of direct and indirect labor required, and calculation of payroll including the benefits of the Colombian law. iii) Calculation of initial investment, working capital, production and administration costs. The net profits comprised a depreciation of 10%, taxes on profits and equity, and inflation as relevant variables for the calculation. iv) Calculation of financial indicators: Net Present Value (NPV), through the sum of the year-to-year profits carried at present value with an attractive minimum rate of 10%, minus the total investment; and the Internal Rate of Return (IRR), verifying the annual projection when the NPV begins to give a positive result to the investment.

Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process has been widely used to evaluate alternatives based on different analysis criteria, where a hierarchical model is constructed to organize information and make decisions regarding an analysis of complementary criteria [15]. In this case, it permits the selection of the best scenario within the three different mixtures evaluated in previous stages.

The three mixtures of substrates were analyzed in a similar manner, and the criteria involved in decision-making were composed of technical, economic and environmental indicators. Each form of exploitation is evaluated in these terms by criterion indicators.

The indicator goes together with the percentage weights for the evaluation of the criterion. Each indicator has a score of 0 to 10, where 10 is the best rating and 0 is the worst. The average ratings vary between 0 and 10 as a linear function. Indicators were grouped into three broad categories: the technical indicators considered were biogas production (m^3/cycle), the indicators for the LCA according to the EPD methodology, and for the economic category the indicators were NPV and IRR. In order to unify the three categories and obtain a single score for each of the mixtures or scenarios, it was considered that the economic, technical and environmental components were equally relevant.

Results and discussion

Technical framework

Piñeros et al [2] presented a market study for the department of Cundinamarca, from where it was obtained the limiting substrate for each mixture, limiting substrate for mixtures 1 and 2 was the fruit residue, while for the mixture 3 was the sewage sludge. Using the information, the compositions of each mixture and considering that the plant is used 80% on average throughout its useful life, the reactors were sized and the amount of biogas to be obtained was calculated with the biomethanation potentials. Table 3. shows the results obtained for each evaluated mixture.

Table 3. Productive aspects evaluated for each mixture.

	Mixture 1	**Mixture 2**	**Mixture 3**
Installed Capacity (Ton)	32.840	61.807	71.752
Reactor volume (m3)	6.148	9.225	9.846
Biogas production (m3)	1231.656	2943.175	3525.078
Potential (KWh)	1961.412	4687.006	5613.687

Thus, In and Outflows were calculated for each mixture to define, dimension and quote the equipment to be used in each of the three processes. The unit processes defined were raw material storage, milling, mixing, fermentation, sludge storage, dehydration, and electric generation. Including, the environmental aspects and emissions generated during each of the proposed processes (see Figures 1-3).

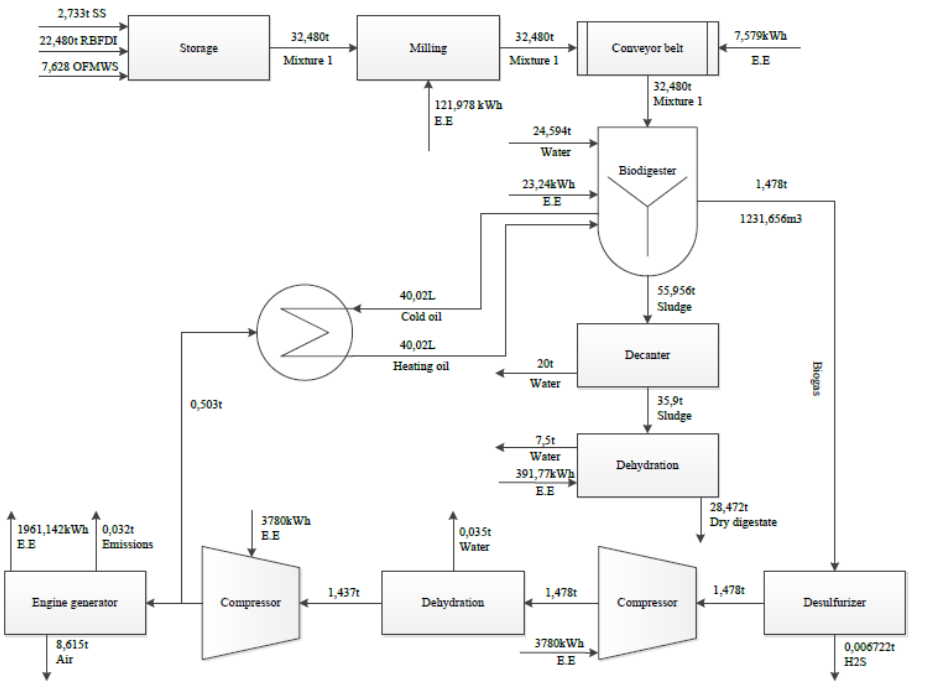


Figure 1. Process flow diagram for Mixture 1.

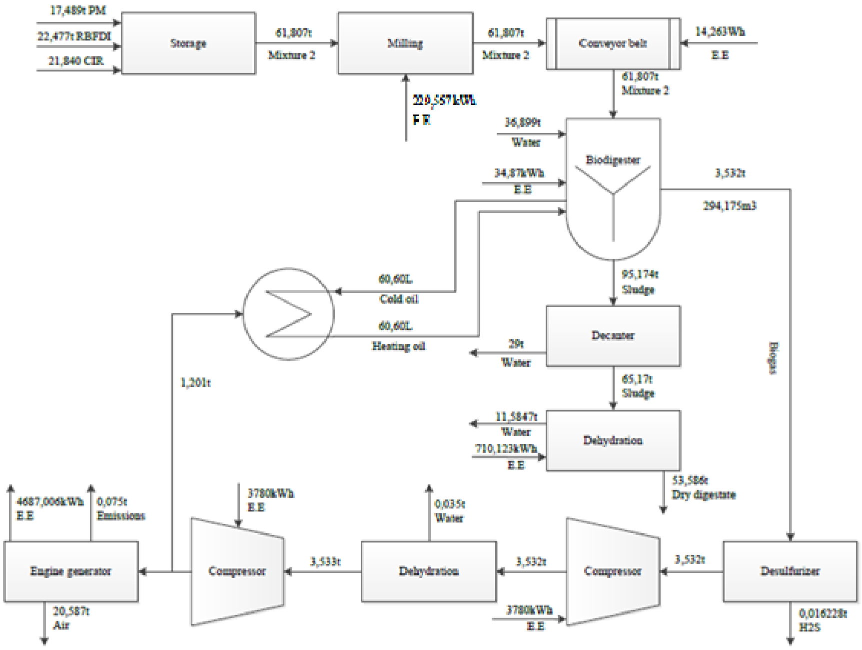


Figure 2. Process flow diagram for Mixture 2.

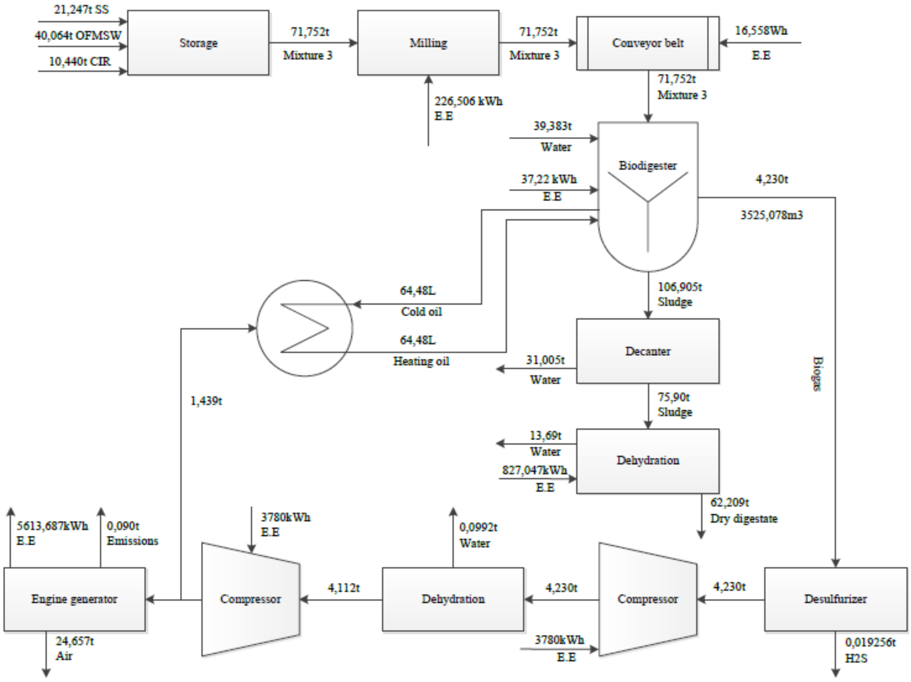


Figure 3. Process flow diagram for Mixture 3.

In this stage, the routes of collection of substrates, from its place of origin to the location of the plant (Soacha); for each evaluated mixture were evaluated. For the Mixture 1, 15 trips were determined to collect all the waste that will be processed per cycle, of which 1 trip is completed transporting 2,733t of sewage sludge waste in a distance of 39.4 km, the transportation of the RBFDI requires 11 trips, the amount of 22,480t covering a distance of 17.9 km per trip, and for the OFMSW 3 trips are made to transport the amount of 7,628t covering a distance of 18.6 km per trip, obtaining a total diesel consumption of 8,346 gallons. In mixture 2, 22 trips would have to be made, for pig manure residues, 6 trips must be made, transporting 17,489t and traveling 37 km for each trip; in the case of RBFDI, 11 trips must be made carrying 22,477t and covering a distance of 17.9 km per trip; and for CIR, 5 trips must be made, covering a distance of 187 km per trip to transport 21,840t, generating a total diesel consumption of 38,683 gallons. While for mixture 3, 23 trips should be executed, of which 8 are completed transporting 21,247t of sewage sludge, traveling a distance of 39.4 km per trip; for the OFMSW, 12 trips must be made to transport 40,064t traveling a distance of 18.6 km per trip, and finally for the CIR

3 trips would be carried to transport 10,440t traveling a distance of 187 km per trip, obtaining a consumption total diesel of 31,411 gallons.

On the milling stage, the equipment selected had the capacity to mill all the waste necessary for a cycle in a maximum of two days. The energy consumption of this stage was evaluated by calculating the hours of operation in each mixture and using the average consumption reported in the technical sheet. Mixture 1 would have an electrical consumption of 121,978 kWh, for the mixture 2 of 229,567 kWh and for the mixture 3 266,506 kWh. The mixture and transport of the waste to the reactor would be carried out in a conveyor belt that would have an electrical consumption of 7.579 kWh for mixture 1, while for mixture 2 it would be 14.263 kWh and for mixture 3 of 16.558 kWh. Once again the energy consumption is greater in the mixture 3 given the volume of waste to be treated in the plant [16].

Once the waste mixtures are transported to the reactor, water and inoculum are added. Two outputs are generated in the reactor: one for biogas and another for digestato. As the biogas comes out saturated and with a high content of H2S, it is first passed through a biofilter to remove most of the H2S and then it is compressed and driven through a tower to remove moisture. These stages of conditioning are necessary to burn the biogas under technical and environmental standards that guarantee the durability of the generator engine. Since a strong pressure drop occurs in the dehumidifying tower, the biogas is again compressed at 8 atm before entering the generator engine. The electric power generated varied depending on the mixture, being higher in mixture 3 with a value of 5613.687 kWh and lower in mixture 1 with a value of 1961.412 kWh. On the other hand, the digestato generated can also be used, for this they have to remove much of the moisture to be used as fertilizer, in the process used a decanter tank and a sludge dehydrator, obtaining as final output a dry digestato, the greatest quantity was produced in mixture 3, being 62.209t per cycle.

Life cycle assessment

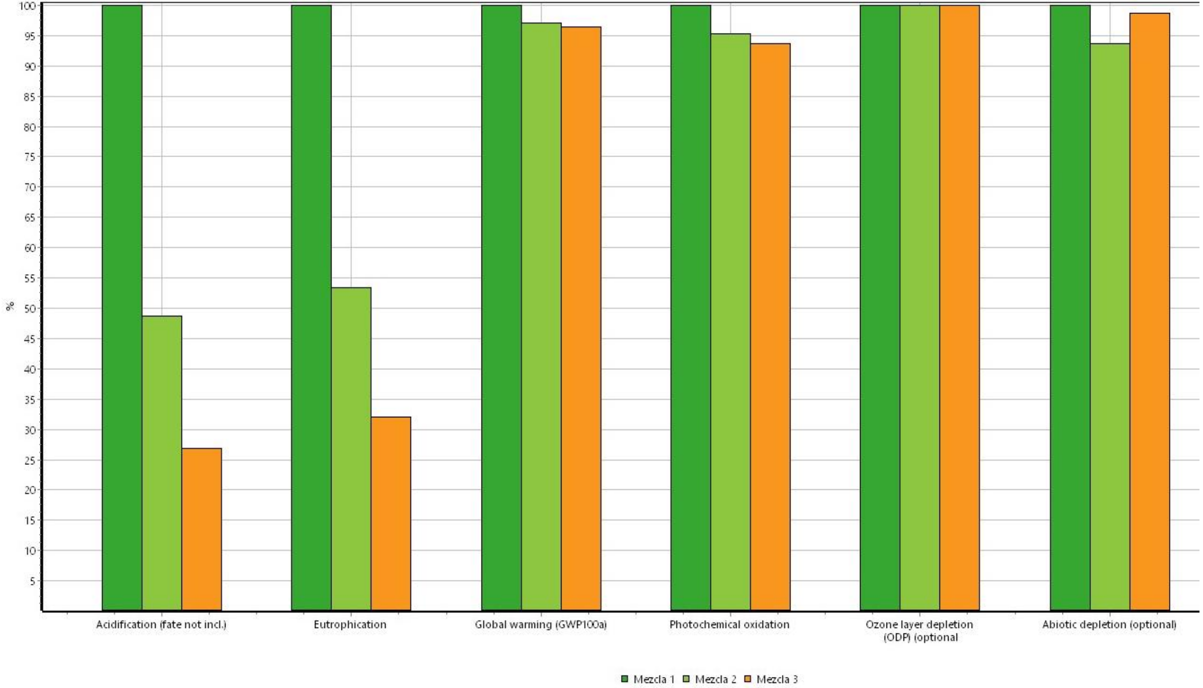
The inventory analysis was based on the inputs and outputs flows of the production processes proposed for each scenario. At this point, the transport and consumption of raw materials and energy, product and co-products such as digest to were evaluated; as well as determining which stages of the process had emissions or discharges. There are discharges in the decanter, the sludge dehydrator, and the biogas dehydrator. In the generator engine, there are air emissions (Table 4.), calculated with the flow of biogas combusted and the characterization of combustion gases presented by Blanco, Santalla, Córdoba, & Levy [17].

Table 4. Atmospheric emission characteristics, from biogas combustion.

Emissions	Mixture 1 (mg)	Mixture 2 (mg)	Mixture 3 (mg)
Benzene	279336.118	667499.205	799477.254
Chloroform	17458.507	41718.700	49967.328
Toluene	1719662.975	4109291.980	4921781.843
Xylenes	1213366.261	2899449.671	3472729.321
Dichlorodifluoromethane	4242417.287	10137644.174	12142060.791
Ethanol	12657417.833	30246057.721	36226313.061
Propane	5499429.817	13141390.596	15739708.433
Butane	5464512.802	13057953.196	15639773.777
Carbon disulfide	192043.581	458905.703	549640.612
Hydrogen sulfide	240054.476	573632.129	687050.765

The inventory analysis made possible to establish that the most relevant environmental aspects are associated with water and energy consumption from non-renewable sources, atmospheric emissions generated by the combustion of biogas and discharge of wastewater from the process. Figure 4. presents the environmental impact profile diagram, a *SimaPro* contrast option was used to compare the mixtures, by the addition of the kg-eq generated in each of the selected potential impact categories. The software assigns the percentage of 100% to the process that has the most significant impact and with this reference calculates the percentage of the other processes. The three mixtures were compared using 1 kWh of electrical energy as reference.

Figure 4. Comparative environmental profile of the three mixtures.



Corresponding to the acidification category, the impact percentage of mixture 1 is 100%, that of mixture 2 is 48%, and that of mixture 3 is 28%. This category of impact consists of the measurement of the deposition of acids released from NOx and SOx to the atmosphere, soil, and water. These emissions could vary the acidity of the environment and thus affect the fauna and flora, produce deforestation and cause harm to human health.

Eutrophication refers to the impacts produced by the presence of high levels of macronutrients (nitrogen and phosphorus). The increase of these proliferates the production of biomass in aquatic ecosystems and leads to the rise of the Biological Demand of Oxygen (BDO). Said oxygen consumption can establish anaerobic conditions that will cause decomposition caused by bacteria that will liberate CH4, H2S, and NH3. The last one disappears in any aerobic life. In this category, the mixture 1 generates the highest environmental impact (100%), followed by mixture 2 (54%) and mixture 3 (33%).

Regarding the global warming aspects, the generation of greenhouse gases from the process associated with mixture 1 was also the highest, followed by mixture 2 (98%) and the lowest was for mixture 3 (94%). Climate change has an impact on the areas of human health, and on the habitat, because the earth absorbs the sun's radiation, this energy is recharged to the atmosphere and resumed in the form of thermal infrared. Part of this radiation is absorbed by gases present in the atmosphere causing warming of the earth's crust, called the greenhouse effect. The gases that generate the highest proportion of this effect are CH4, N2O, and CFCs.

For the photochemical oxidation category, it was found that mixture 1 generates the most significant impact, followed again by mixture 2, with mixture 3 having the least impact. Photochemical oxidation is generated from the influence of radiation: NOx react with COVS to produce tropospheric ozone. The decrease in the ozone layer causes an increase in the amount of UV radiation, which reaches the earth. These radiations affect human health, the natural environment, and agricultural production. In the deterioration category of the ozone layer, it was found that the three mixtures have the same amount of emissions.

Finally, it was found that in the category of abiotic deterioration, mixture 1 generates the most significant impact, followed by mixture 3 (98%) and mix less 2 (94%). In general, the environmental performance of mixture 3 is better in almost all impact categories evaluated.

Economic assessment

Starting from the mass and energy balances of the elaborated block diagram, the equipment to be used in each of the three processes was identified, dimensioned and quoted. Table 5. shows the prices of the equipment for the three mixtures evaluated. The value of some equipment is different for each mixture according to the required capacity since it varies with each of the substrates. The laboratory equipment, the physical plant, and the truck maintain the same price for the three mixtures, like the payroll, the value of space in the industrial zone and public services, taking into account that the project will be located in the municipality of Soacha.

For the calculation of the payroll required in each project, the operations to be carried out in the batch processes were taken into account. It was calculated that with nine people all the necessary tasks could be fulfilled: a manager, a professional in engineering, a mechanical technician, an environmental practitioner, four operatives and a person for general services. With this information, a monthly allocation was made for each profile, and the benefits of Colombian law were evaluated by multiplying the salary value by 1.6. For the year 2018, the labour costs obtained were COP 414,720,000. The annual correction was made using the average CPI for the last five years.

Additionally, the costs associated with public services were taken into account, which was budgeted using rates for the industrial sector. The use of electricity, water, internet, and telephony was contemplated. Information from the mass and energy balances were used to calculate the consumption of water and electricity, as well as the consumption associated with the personnel that works daily in the facilities. The water consumption in the process is mainly for the reactor and equipment washing.

To obtain the economic indicators of each of the three processes, costs and revenues were projected for ten years. The depreciation of the equipment was evaluated using the linear methodology of 10% per year up to salvage value of 40% [18]. The taxes to the patrimony were considered of the 4/1000 and one of the utilities of 35%. The revenues from the processes are mainly due to the production of dry digestato and electrical energy. For its part, expenditures are composed of service expenses, payroll, diesel for transport and maintenance of machinery. Raw material costs were considered only for pig manure since it is the only substrate that currently has commercial value [2].

The NPV was calculated for each year and each of the mixtures under study. The NPV was calculated by adding the total profits and the book value of the assets, both carried to 2028 with an attractive minimum rate of 10%, subtracting the total investment. TIR values obtained show us that mixture 1 has only one point above the value of the minimum attractive rate. The results obtained converts the process of mixture one into a risky investment that probably after the detailed design of the process and putting into operation results in an expensive option. The calculation sheet elaborated for the economic evaluation was used in order to observe if the profitability improved by charging for the disposal of the waste that makes up the mixture to the producers, however, the profitability did not improve significantly.

On the other hand, mixtures 2 and 3 obtained very favourable results, which makes them candidates to move on to the elaboration of a detailed engineering study and its subsequent start-up. The significant difference in the profitability of the mixtures is due to the strong economy of scale of these processes. A small difference in the capacity to process is reflected in a vast difference in the IRR and NPV at ten years of the project.

Table 5. Results for the economic evaluation and analytic hierarchy process.

	Mixture 1	**Mixture 2**	**Mixture 3**
Total initial investment	$ 2.580.118.254	$ 2.605.082.104	$ 2.607.350.904
NPV	$ 134.720.193	$ 4.184.207.848	$5.498.301.525
IRR	0,11	0,32	0,39

Analytic Hierarchy Process (AHP)

Results of the hierarchy process analysis are shown in Table 6. The mixture 1 has the lowest score for the process, since the environmental criterion resulted in an average of 1,429, while the mixtures 2 and 3 have superior environmental performances, scored with 8,161 and 9,048 respectively. In addition, for the technical and economic criteria, the result obtained for Mixture 1 was zero, because it presents the lowest level of biogas production and lower profitability. For mixture 2, the technical and the economic criterion reports 7,463 and 8,342 each. It resembles the values for the technical and economic criteria of mixture 3, being this the best alternative; the result obtained was 10 in both qualifications as a result of high methane production and the project in this scenario has the higher profitability.

Table 6. Analytic hierarchy process results.

	Mixture 1		Mixture 2		Mixture 3	
Environmental performance	**Evaluation value**	**AHP score**	**Evaluation value**	**AHP score**	**Evaluation value**	**AHP score**
Terrestrial acidification	100	0	49	6,986	27	10
Fresh water eutrophication	100	0	54	6,986	33	10
Climate change	100	0	97	7,5	96	10
Photochemical oxidation	100	0	95,2	8	94	10
Ozone depletion	100	10	100	10	100	10
Abiotic depletion	100	0	94	10	98	3,3
Fossil flues depletion	100	0	51	7,778	37	10
Average		1,429		8,179		9,043
Technical framework	**Evaluation value**	**AHP score**	**Evaluation value**	**AHP score**	**Evaluation value**	**AHP score**
Biogas production (m3)	1231,656	0	2943,175	7,463	3525,078	10
Average		0		7,463		10
Economic assessment	**Evaluation value**	**AHP score**	**Evaluation value**	**AHP score**	**Evaluation value**	**AHP score**
Total initial investment	$ 2.580.118.254	0	$ 2.605.082.104	7,5	$ 2.607.350.904	10
IRR (years)	7	0	1	10	1	10
IRR	0,11	0	0,32	7,5	0,39	10
Average		0		8,33		10
Total average		**0,476**		**7,992**		**9,681**

Conclusions

The best mixture to generate electric energy is mixture three since it generates the most significant amount of biogas at 56401,248 m3 per year. Additionally, mixture 3 obtained the best results in the economic study with an NPV for the last year of COP 5,507,646,009 and an IRR of 38.99%. Regarding the environmental analysis, it was also found that the mixture that generates less potential environmental impacts is mixture 3, closely followed by mixture 2. On the other hand, the amount of electrical energy that can be generated depends more on the size of the plant than on the biomethanation potentials. However, it is vital to bear in mind that the plant's incomes were mainly due to the sale of dry digestato and not due to the generation of electric power, this means that attention must be paid to the composition and quality of this product.

After conducting the LCA using the EPD methodology and the *Ecoinvent* databases, it was observed that the environmental impact is also associated with the size of the plant. These results are mainly because many operations generate the same impact with low production as with high production, when increasing capacity, there was a greater volume of a product without incurring in a significant increase in the environmental impact generated.

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References

[1] H. Escalante Hernández, J. Orduz Prada, H.J. Zapata Lesmes, M.C. Cardona Ruiz, M. Duarte Ortega, Atlas del potencial energetico de la biomasa residual, 2011. https://biblioteca.minminas.gov.co/pdf/ATLAS%20POTENCIAL%20ENERGETICO%20BIOMASA%20RESIDUAL%20COL.%20UPME.pdf.

[2] V. Piñeros, K. Melo, J. Mosquera, A. Santis, M. Hernandez, I. Cabeza, P. Acevedo, Economic feasibility and environmental impact assessment of anaerobic co-digestion processes in Colombia, in: Elsevier, 2018.

[3] I. Cabeza, M. Thomas, A. Vásquez, P. Acevedo, Anaerobic co-digestion of organic residues from different productive sectors in Colombia: Biomethanation potential assessment, 49 (2016) 385–390. doi:10.3303/CET1649065.

[4] J. Mosquera, L. Valera, A. Santis, S. Villamizar, P. Acevedo, I. Cabeza, An empirical model for the anaerobic co-digestion process of pig manure, sewage sludge, municipal solid waste, residues from bottled fruit drinks industry and cocoa industry residue, in: Elsevier, 2018.

[5] R.J. Patinvoh, O.A. Osadolor, I. Sárvári Horváth, M.J. Taherzadeh, Cost effective dry anaerobic digestion in textile bioreactors: Experimental and economic evaluation, 245 (2017) 549–559. doi://doi.org/10.1016/j.biortech.2017.08.081.

[6] Cámara de Comercio de Cali, Bioenergía Iniciativa Cluster, Santiago de Cali, 2017.

[7] J. Vasco-Correa, S. Khanal, A. Manandhar, A. Shah, Anaerobic digestion for bioenergy production: Global status, environmental and techno-economic implications, and government policies, 247 (2018) 1015–1026. doi://doi.org/10.1016/j.biortech.2017.09.004.

[8] H. Escalante, L. Castro, P. Gauthier-Maradei, R. Rodríguez De La Vega, Spatial decision support system to evaluate crop residue energy potential by anaerobic digestion, 219 (2016) 80–90. doi://doi.org.bdatos.usantotomas.edu.co/10.1016/j.biortech.2016.06.136.

[9] C. Cowley, B.W. Brorsen, Anaerobic Digester Production and Cost Functions, 152 (2018) 347–357. doi://doi.org.bdatos.usantotomas.edu.co/10.1016/j.ecolecon.2018.06.013.

[10] F. Xu, Y. Li, X. Ge, L. Yang, Y. Li, Anaerobic digestion of food waste – Challenges and opportunities, 247 (2018) 1047–1058. doi://doi.org/10.1016/j.biortech.2017.09.020.

[11] F. Mayer, R. Bhandari, S. Gäth, Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies, 672 (2019) 708–721. doi://doi.org/10.1016/j.scitotenv.2019.03.449.

[12] M. Garfí, L. Castro, N. Montero, H. Escalante, I. Ferrer, Evaluating environmental benefits of low-cost biogas digesters in small-scale farms in Colombia: A life cycle assessment, 274 (2019) 541–548. doi://doi.org/10.1016/j.biortech.2018.12.007.

[13] I.S. Organization, ISO (International Standard Organization) Environmental Management - Life Cycle Assessment - Principles and Framework, International Standard ISO 14040, Geneva, Switzerland, 2006.

[14] A. Becerra Q., Evaluación de la sustentabilidad del aprovechamiento del bagazo de caña de azúcar en el Valle del Cauca – Colombia a partir del Análisis de Ciclo, Universidad Distrital Francisco José de Caldas, 2015.

[15] P. Acevedo P., Herramienta de análisis de alternativas de producción incorporando el ACV "cuna a cuna" a los métodos tradicionales. Comparación de biodiesel de palma e higuerilla., Universidad Industrial de Santande, 2012.

[16] A. Bomboí, Pretratamiento del biogás procedente de la digestión anaerobia de lodos de EDARs para su posterior valorización energética, in: 2014.

[17] G. Blanco, E. Santalla, V. Córdoba, A. Levy, Generación de electricidad a partir de biogás capturado de residuos sólidos urbanos: Un análisis teórico-práctico, 2017.

[18] W. Dussán Salazar, Limitación a la deducción por depreciación, (2017). https://www.consultorcontable.com/depreciaci%C3%B3n-niif-impuestos/.