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Technical and Environmental Analysis of Large-Scale Pig Manure Digestion through Process Simulation and Life Cycle Assessment

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The biogas and by-products production from anaerobic digestion of pig manure was evaluated technically, economically, and environmentally in an industrial park in Bogotá, Colombia, in order to generate economic opportunities and to reduce environmental impacts. Mass and energy balances were performed using data from literature and developing a simulation of the AD process in Aspen Plus software based on stoichiometric balances. The environmental evaluation of this process was developed using LCA methodology. Also, the economic viability of the process was evaluated by calculating the internal rate of return and the net present value considering 10 years of life of the plant and equipment. The results of the environmental evaluation show that the stages of transport, and consumption of electrical and thermal energy contribute to the categories of acidification, abiotic, and ozone layer depletion, for both scenarios of interest according to the allocation of the final product. Furthermore, it is established that the project is viable as it has an internal rate of return of 26% and a payback time of 5 years, according to the results of the economic evaluation.

1. Introduction

The anaerobic digestion (AD) is a feasible response to Colombia's energy demand in order to increase the percentage of biogas participation within the energy matrix through the use of the large amount of biomass available; according to Piñeros, V.*et* al, (2018), there is availability of substrates such as pig manure (PM) that has a high potential for bio-methanation. In Colombia, currently the increase in pig production generates approximately eight million tons of manure per year in just one department. Then, bioprocesses can be one of the answers within the Nationally Appropriate Mitigation Actions for the mitigation of greenhouse gases (GHG); promoting the generation of biogas of agricultural origin for energy use, through the recovery of waste generated in this economic sector (Ministerio de minas y energía, 2019). Since the AD process is not unrelated to the scale's economy, it is necessary to engage large amounts of organic residues in one place to improve profitability, which might represent a threat to the environment in which they are disposed of, treated, and transformed. For this reason, possible environmental impacts are being evaluated, using methodologies such as process simulation and its environmental analysis. The different scenarios can be modelling by scaling processes, allowing the generation of balances through the data obtained; and the environmental analysis can be carried out using Life Cycle Assessment (LCA) methodology, where potential environmental impacts are quantified and identified from the beginning to the end of a process. This study of biomass conversion and its uses aims to determine the technical, economical, and environmental viability of producing electric energy (EE) through the biogas generated by the AD of pig manure. It also evaluates the scenario in which the manures of several pig farms in the department of Cundinamarca are coupled, and an electric

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power generating plant which could be built in an industrial park located near Bogotá, including in the analysis the production of digestate to be marketed as fertilizer.

2. Methodology

2.1 Mass balances and simulation of the process

The available PM in the department of Cundinamarca was calculated according to the study by Piñeros, V. *et* al,(2018). The first unit process included the harvesting and transportation of the raw material, which included diesel fuel consumption calculations, according to Garbs & Geldermann, (2018). A 32 tons of load capacity and Euro 3 emission standard truck was defined. The following unit processes data were based on the simulation of an AD large-scale process, carried out in Aspen Plus. For this, a stirred semi-batch reactor was considered, with 21 days, in mesophilic conditions (35 °C), atmospheric pressure, and with the following characterization of the PM: 22.83% of TS, 19.79% of VS, 4.98 g/L of COD, 1.88% of total Kjeldahl nitrogen and 82.30% of content of organic matter (Amado et al., 2021). From the simulation results, the production and sizing of the equipment are obtained. It was considered that the reactors are fed with conveyor belts, which collect the material stored in hoppers. Biogas requires a process of desulfurization and dehydration before being transformed into electrical energy. This process is carried out in a coupled unit, which has a compost biofilter and a dehydrator with removal efficiencies between 80 and 97% (Navarro et al., 2007; Vikrant et al., 2018). Once the biogas has been treated, with removal efficiencies between 80 and 97%.in a combustion engine by increasing the pressure to the inlet of the engine. The electrical energy generated was calculated based on Eq. (1)-(2) (Espejo et al., 2019).

$$Electrical\ energy\ (KW) = Batch\ production\ (m^3CH_4) * Biogas\ energy\ (KWh/m^3)\ *\ 0{,}65 * 0{,}35 \quad (1)$$

$$Batch\ production\ (m^3CH_4) =\ BMP\ (m^3CH_4/Ton\ VS)\ *\ ton\ VS_{residuo} \quad (2)$$

Where 0.65 is the factor to determine the amount of biogas available to produce electrical energy, and 0.35 is the efficiency factor of the generator motor. The bio-methanisation potential (BMP) of the PM used was 437.33 m^3/CH_4/ton VS (Rodríguez et al., 2017) and the specific heat of the biogas (6 KWh/m^3), based on the methane fraction (0.5-0.6) (Indrawan et al., 2018). To calculate the combustion gases, the concentrations measured in the report of the Inter-American Development Bank (Blanco et al., 2017) were used. Furthermore, CO_2 and CO emissions were taken from the Ecoinvent 3 database and from the technical report by Nielsen et al., (2010) respectively. The digestate, which leaves the biodigester as a muddy mixture of PM with water, was treated in the decantation and centrifuge processes to remove the water. In the decanter, 80% of water is poured with soluble substances such as fatty acids, amino acids, carbon dioxide, among others. The remaining sludge is transferred to a centrifugal dehydrator that maintains 80% humidity in the final digestate.

2.2 Economic evaluation

The economic evaluation was carried out based on determining the viability of the AD process of PM for the generation of electrical energy and digestate. For the development of this, a 10-year cash flow (2019 to 2029) was calculated considering income, from the sale of AD products, the costs of raw materials, and necessary supplies, maintenance, and payroll. Additionally, the depreciation of the equipment, the annual taxes (profit and equity), the total investment of the project and the salvage (20% total investment of the equipment). Finally, viability was determined from the net present value (NPV) and the internal rate of return (IRR).

2.3 Life cycle assessment

Following the International Organization for Standardization (ISO 14040), this study uses the LCA methodology which proposes four main stages: definition of aim and scope, life cycle inventory, life cycle impact assessment, and finally interpretation (ISO, 2006). The aim of this work was to evaluate the generation of electricity and digestate from the biogas resulting from AD of PM, and to identify and quantify the potential environmental impacts of two possible scenarios based on the data obtained from the simulation of this process. For this, a door-to-door approach is established where the necessary raw materials and the required industrial services were taken from the EcoInvent 3 databases.

The starting point of the established study was the transport of the PM, from the municipality of San Antonio de Tequendama to Bogotá, and ends with the generation of electric power and digestate. The first scenario is based on a 100% allocation for biogas since the study has the purpose of generating electrical energy. For this scenario, a functional unit (FU) of 1 kWh of electrical energy generated was selected. For the second scenario, the allocation percentage is changed to 100% of the digestate obtained; since, in the results of the

economic evaluation, most of the income corresponds to its sale. The selected FU is 1 Kg of digestate produced.
For the LCIA, SimaPro software was used and the inputs and outputs were entered, the latter being the products of the process or environmental aspects (wastewater and emissions), obtained in the construction of the mass and energy balances. The LCIA profile was estimated using the CML baseline methodology for the following impact categories: acidification (AC-KgSO_2eq), abiotic depletion (AbD- KgSbeq), eutrophication (EP-gPO_4eq), climate change (GWP-KgCO_2eq), ozone layer depletion (OLD- KgCFC-11eq) and photochemical oxidation (PO-KgC_2H_4eq).

3. Results

Figure 1 shows the process diagram, where the black lines show the flow of mass currents, while the red lines represent the energy consumption of the equipment used. The values shown are calculated for a 21-day anaerobic digestion modelling process.

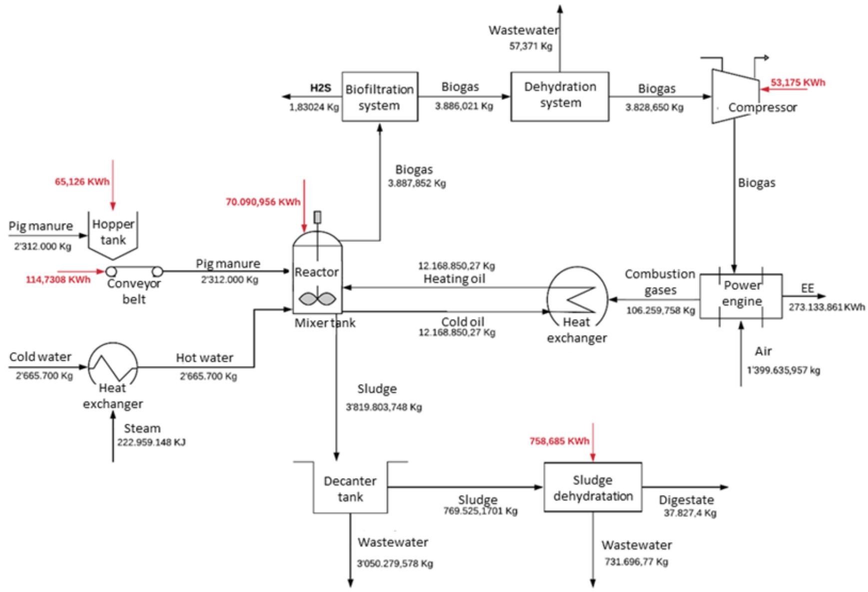

Figure 1: Diagram of AD process for PM

A distance of 32.5 km and 73 trips were estimated for the collection of the PM of a batch, from the pig farms to Bogotá. The collection of the PM is done once before each batch begins and stored in four hoppers with a capacity of 850 m^3 each. The stored biomass is transported to the reactors using two conveyor belts. Due to the large amount of PM for AD, it was established that the process will be carried out in two biodigesters, each of 3702 m^3. From the first treatment given to biogas, a removal of H_2S (g) is obtained, the value of which was excluded from the evaluation due to the low concentration obtained. In addition, for obtaining electricity, two internal combustion engines of 300 kW each with their respective compressor are used. It is important to consider the use of heat exchangers. The first one has the functionality of increasing the temperature of the water entering the stirred reactor, so that the temperature conditions are obtained for AD reactions to be carried out. The second exchanger takes advantage of the combustion gases from the generator engine to heat thermal oil.

3.1 Economic evaluation

The economic evaluation of the process was carried out based on 10-year cash flow, in which the values of the income from the sale of electricity and digestate were calculated. Additionally, the process costs considered correspond to the payroll, equipment maintenance, and water consumption and price (Ministerio de Vivienda, Ciudad y Territorio, 2010). There are also the costs of purchasing PM, the consumption of oil to heat the reactor (Priboloc, 2019), and diesel for the truck and forklift (Ministerio de minas y energía, 2019). The price of energy was taken the same as both the sale price and the cost and corresponds to the reported market value of the (UPME, 2019). Also, the consumption of electrical energy for lighting was taken from EPM data (EPM, 2019). The quantity data for income and costs were taken from the results obtained in the balances, and their value increased annually based on the CPI (Sintraprevi, 2018); for which the average of the index was taken from 2015 to 2018. The results show, the sale of the digestate represents the highest income for the project, while the highest costs are reflected in the purchase of PM. It was established that the depreciation of the equipment and the salvage of the project is 10% and 20% respectively, of the total investment less the cost of the land. Taxes calculated are taxes on profits (33%) and wealth tax. Taking these data into account, the net operating profit (UNO) was calculated, which was subsequently used together with the minimum attractive rate TAM (10%) and the value of the corrected equity, to estimate the annual NPV and the IRR. The results of the economic evaluation shown that for a purchase value of $ 14 per Kg of EC and a sale value of digestate of $ 2000, the recovery time of the project investment (equipment and land) is five years. On the other hand, an IRR of 26% was obtained, this being higher than the TAM, which indicates that the project is profitable and that apart from recovering the investment, profits will be generated.

3.2 Life cycle assessment

3.2.1 Life cycle impacts assessment LCIA

Figures 2 shows the contribution of the stages of the AD process to each of the impact categories evaluated for the first and second scenario proposed. Figure 2a shows that in the first scenario the stages that contribute to the evaluated impact categories are the generation of electrical energy, PM transport, process water consumption, temperature increase of the water entering the biodigester (steam) and energy consumption of the process, which for this scenario, the equipment that consumes energy are the hopper, the conveyor belt, the biodigester agitators and the compressor.

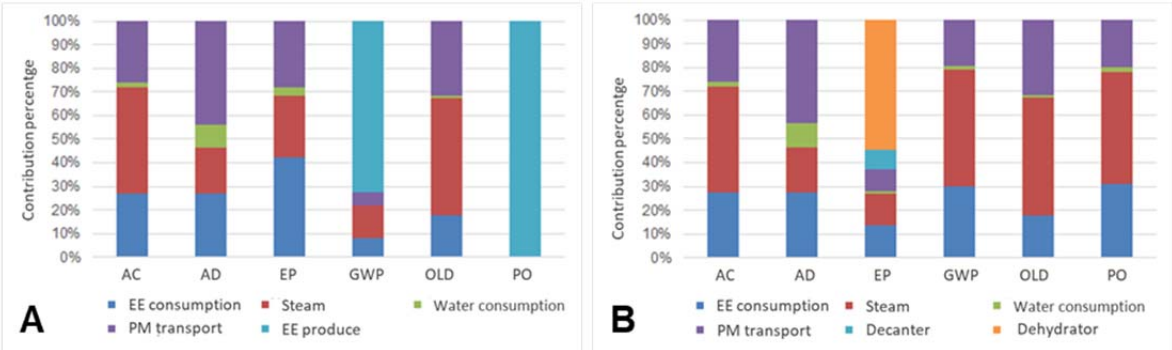

Figure 2: Contribution of stages to the impact categories in (a) scenario 1 (biogas); (b) scenario 2 (digestate)

According to the LCIA profile of the first scenario evaluated, the AC and OLD categories present similar contributions, since the consumed steam stage is the one that most influences these categories with 44.8% and 49.7% respectively, followed by the PM transport and the electrical energy process. The AC contribution is assigned to the composition of the emission gases (ammonia, nitrogen oxides and sulfur oxides), impacting the acidity of the air (Antón, 2004). Those gases are probably generated in the processes of burning of fossil fuels and the generation of electrical energy. For the OLD category, the contribution is due to the emissions of chlorofluorocarbons and halons, possibly generated in the production of diesel, electric power and steam, which are the precursors of the decrease in the ozone layer (Antón, 2004). The stages of PM transport, consumption of electrical energy in the process and the steam consumed are those that contribute significantly to category AbD with 43.7%, 27.2% and 19.2% respectively. This is related to resource depletion factors such as gold, cadmium, copper, silver and zinc (Antón, 2004) due to the extraction of fossil fuels necessary for the production of diesel, the generation of electrical energy and the production of industrial steam. For the EP category, the stages that contribute significantly are the consumption of electrical energy (42.2%), the transport of PM (28.1%) and the steam generated (26.4%), due to the wastewater and increase of the chemical demand (oxygen, nitrate, nitrogen, and phosphate in the water) which generates an increase in algaes. For the GWP and PO categories, the stage that contributes the most is the generator engine or the generation of electrical energy with 72.6% and 99.5% respectively, due to the combustion of biogas within the engine, which generates emissions of GHG like CO_2 and VOCs like butane, propane and toluene, which react with nitrogen oxides and produce tropospheric ozone (Antón, 2004).

Figure 2b shows the stages of contribution to benefits and/or environmental impacts, which are PM transport, water consumption, temperature increase to the water entering the biodigester (steam), energy consumed in the process, settling and dewatering of sludge for the second scenario. Furthermore, the steam used to heat the water entering the digester has high influence on at least four of the six impact categories, highlighting the GWP and OLD with percentages impact of 49.3% and 49.6% respectively. This is due to the emissions of compounds such as CO_2, CH_4 and chlorofluorocarbons, which increase GHG and contribute to the degradation of the ozone layer (Antón, 2004). These emissions are connected with the fossil fuels used in the harvesting. This case also applies to the consumption of electrical energy and transportation, as they contribute to the impacts generated in these categories. On the other hand, steam does not have the greatest impact on the category EP.

The greatest contributions to macronutrient impacts are found in the dehydrator tank when generating discharges of substances such as ammonia together with phosphate and nitrogenous compounds. After the review of the substances present in the discharge of this stage, a high presence of glucose was found, which together with the above mentioned substances, would contribute to the increase in biomass production in the water source, which brings with it a decrease in available oxygen, causing anaerobic conditions in the environment (Antón, 2004). Regarding the PO and AC categories, the stage that presents the greatest contribution to impact, after steam, is the consumption of electrical energy, with a percentage of 30.8% and 27.4%; This is due to the NO_x and sulfur emissions to the atmosphere that increase the production of photo-oxidants, which cause, on the one hand, in the presence of VOCs, the generation of tropospheric O_3, and on the other hand, the decomposition of acids causing acidification of the medium (Antón, 2004).

For the AbD category, the stage that presents the greatest contribution is the transport of PM with a 43.5% value related to resource depletion factors such as cadmium, chromium, copper, gold and lead (Antón, 2004); extracted to obtain the necessary infrastructure for the transport and obtaining of electrical energy. According with the analysis of the scenarios, the same behaviours are send for AbD, AC and ODP, resulting on the use of steam, PM transport and energy consumption. As the other scenarios differ based on the allocation, a greater air damage is generated when AD to energy generation; and water and soil depletion when AD to digestate. According with the Mano et al. (2019) and Lijó et al. (2014) results the transport, as a unit process stage, generates an important contribution in the OLD, AC and AbD categories for CO_2, NH_3, nitrogen oxides and sulfur oxides. In addition, contributions to ozone depletion (caused by the production of diesel), eutrophication of fresh water (influenced by the production of machinery) and formation of photochemical oxidants (affected by the combustion of diesel) respectively. De Vries *et al.* (2012), conclude that this stage contributes little in the category of GWP in AD of CD. These results coincide with those obtained in the present study, since, for the two scenarios evaluated, transport contributes in these categories, especially in AbD. To increase bioenergy with mono-digestion, additional processing can be applied to the PM as separation or pretreatment, which would help to concentrate the available organic matter to increase the efficiency of the AD process evaluated in this study, after an analysis considering the increases in energy demand (De Vries et al., 2012). Mano et al. (2019), affirm that the impacts of AD plant depend on several factors such as technologies or operating practices. In this study, a starter heat exchanger is used, which uses steam to heat the water entering the biodigester, which, as evidenced in the two-scenarios, affects in almost all categories and significantly. This is an operational practice that is not present in all AD plants. The electric energy consumption takes energy from the national grid and contributes to OLD and EP categories with a low percentage for both. Different studies conclude that electric power generation contributes significantly to the GWP and PO categories (Lijó et al., 2014; Mano et al., 2019) as shown in this study. Regarding the digestate generation process Mano et al. (2019), affirm that the separation of the liquid phase and the solid phase, reduces the ammonia content, a situation that was evidenced in this study, because in the discharges generated in the decanter tank and centrifugal dehydrator, the soluble substances, among these ammonias, they are removed, leaving a low content of it in the digestate.

4. Conclusions

This study contributes to the technical-economic and environmental study of the AD process to produce biogas from residual biomass. The results show that in the department of Cundinamarca, Colombia it is feasible to install a plant with a processing capacity of 3.2 tons of biomass where according de LCA, the highest contribution are the transport of the PM, the consumption of electrical energy and the use of steam. Even though the data of these stages were calculated in relation to the simulation of the process, the specifications of these steps were taken directly from the inventory of the SimaPro software; therefore, these are included indirectly in the analysis. The results present an alternative treatement to the conventional handling of this agro-industrial waste, without additional processing and the process is environmentally viable due to the fact that similar results were obtained from such studies, where a real scenario of production of electrical energy from AD was compared with other forms of obtaining energy, the former being the best alternative for reducing GHG and of the impacts in the GWP, PO, OLD and AbD categories.

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