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Sustainable Design of Microbiorefineries from Cassava and Rejected Banana Coupled with Renewable Energy in Colombia

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Interest in decentralized small-scale biorefining has increased due to the economical, ecological, and social benefits that these alternative business models possibly bring, especially to developing countries. In this research, two microbiorefineries were conceptually designed in the context of the Colombian Caribbean region. One from cassava produces several products such as cassava starch, calcium citrate, and biogas. The other uses rejected bananas to obtain green banana flour, calcium lactate, and glucose syrup. Design rules for small-scale biorefinery processes developed by previous authors were considered and supported on simulations, literature data, local raw material costs, and equipment quotes to determine the minimum processing scale for economic feasibility (MPSEF) for each case. Aspen Plus® software was used for the simulations in tandem with MATLAB for the calculation of the MPSEF. Values of 4.2 and 22.4 t/day were found for the cassava and rejected banana biorefineries respectively. Applying the WAste Reduction algorithm (WAR), generated potential environmental impacts (PEI) values of -13.1 and -9.4 PEI/h for cassava and rejected banana were obtained, suggesting that these process topologies have an environmentally friendly performance. In addition, an economic evaluation of an energy supply system assisted by solar energy was carried out, based on a non-linear programming optimization model solved with LINGO® software, finding that economic performance in terms of IRR is reduced by 24.9% when solar collectors provide 60% of the energy requirements.

1. Introduction

Over the last decade, research and experimental prototypes for the development of small-scale biorefineries have begun to emerge with the aspiration to promote a circular economy and take advantage of the benefits generated by small-scale processing of biomass in the agricultural sector. Raw material transportation costs are greatly reduced with the local processing of biomass, where by-products are also used for applications such as fertilization and soil adaptation (Bruins and Sanders, 2012).

The term microbiorefinery (MBR) has originated in this work by drawing a parallel between the biorefinery concept and the craft beer plants known as microbreweries, which usually have a production capacity of about 10% of a commercial-size brewery. It is still difficult to define “small-scale” as this depends on the type of process, products, or feedstock. A useful parameter is the “minimum processing scale for economic feasibility” (MPSEF), defined in the work of Serna-Loaiza et al. (2018), which is the scale at which the net present value of the plant is zero at the end of its lifetime, meaning that above this scale the plant could be profitable.

Integration into renewable energy sources for microbiorefineries could be important because most of the rural zones, which contain the agricultural hubs, in Colombia are not connected to the national electric energy grid, and use mostly fossil fuels for power generation. Over the last decade, there have been several research works in this area, for example, Tora and El-Halwagi (2010), proposed a method to calculate the solar power contribution of an integrated system minimizing the total annualized cost of the plant.

The aim of this work is to conceptually design and assess two microbiorefineries, one using cassava as raw material to produce starch, calcium citrate, and biogas, and the other using rejected bananas to obtain green banana flour, calcium lactate, and glucose syrup. Additionally, integration to solar power in the Colombian Caribbean region is analyzed to assess its technical and economic feasibility.

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2. Methods

Cassava and banana are the crops with the highest production in the Colombian Caribbean region, with 1,003,969 and 596,239 tons per year in 2020 respectively (Ministry of Agriculture, 2020). For this reason, they were selected for the design of small-scale biorefineries in this study. Rejected banana is the name given to the fraction of banana crops that do not meet export specifications, thus approximately one-third of this banana is considered waste, which is often disposed of in sanitary landfills generating contamination. Considering the design rules mentioned in Bruins and Sanders (2012), products with proven economic feasibility for small-scale production and that come from primary biomass, such as cassava starch and banana flour were selected.
Aspen Plus® software was used to solve the mass balances and to gather the thermodynamical properties of the streams. The NRTL thermodynamic model was selected as global properties method with some physicochemical properties for the biomass taken from Wooley and Putsche (1996). In addition, SOLIDS property method was used to model bulk solids handling. MATLAB® was used to calculate the equipment capacity and thermal and electrical power requirements, which lead to the capital and utilities costs estimation. Finally, using the same software, an economic assessment was made for a range of raw material processing rates to estimate the MPSEF.

2.1 Cassava MBR process description

The process begins with the feeding of the peeled cassava roots to a grating machine where the root is crushed to obtain fresh pulp. This pulp is combined with a stream of water in an extractor to separate the cassava bagasse that contains most of the fiber and is retained through a sieve mesh at the bottom, letting out the slurry that contains the cassava starch (Da et al., 2008). Subsequently, the slurry is transported to a sedimentation tank in which the starch granules and excess water (which still contain starch and fiber residues) are separated. This wet starch is finally sent to a drying stage.
The cassava bagasse generated in the extraction stage is fed to a tank with heating and agitation for the gelatinization process that occurs at 80°C for 40 minutes and in which the bagasse is conditioned for better use in fermentation. After that, it is transported to a rotary drum-type fermenter, where solid-state batch fermentation of cassava bagasse is carried out, using the fungus *Aspergillus niger LPB 21,* at a controlled temperature of 28°C for 4-5 days (Prado et al., 2005). The fermented broth is filtered and then taken to a conical reactor where it is placed in contact with calcium hydroxide to generate the precipitation reaction at a temperature of 50°C until a pH of 7-7.2 is reached. The precipitate that contains calcium citrate is separated and dried at a temperature of 60°C in a hot air convection dryer, where a final product with a moisture content of less than 8% is obtained.
Biogas is produced by anaerobic digestion in a covered lagoon-type biodigester with high-density polyethylene (Santos et al., 2017), where residues of starch and fiber from the sedimentation tank and cassava peels are used as substrates. The produced biogas is transported through an underground pipeline to a gas scrubber with process water for H_2S removal. As showed by Walozi et al. (2016), to lower costs in the gas washing stage, neither biogas nor washing water are not pressurized, and also operates with an L/G ratio of 0.75, with these conditions it is possible to obtain a purity of 80% v/v in methane in the biogas.

2.2 Rejected banana MBR process description

Green bananas are passed through a hot water tank at 50°C for 5 minutes to facilitate their manual peeling on the conveyor belt. After peeling, the fruit is submerged in a tank with a 0.3% sodium bisulfite solution as a disinfectant and preservative agent. The fruit is cut into slices of controlled thickness, which are dried at a tray dryer in which the humidity is removed at 60°C for 8 h until it reaches 4 – 6% (da Mota et al., 2000). The dried banana slices are sent to a mill to obtain flour which is sifted to obtain the desired granulometry.
For the production of calcium lactate, banana peels are passed through a grinder and dried. Subsequently, they are fed to the fermenter where they are mixed with water until reaching a concentration of 10% banana peel and necessary nutrients are also added (Mufidah et al., 2017). The fungus *Aspergillus awamori* is initially inoculated, with which the hydrolysis of the substrate for the production of fermentable sugars begins at a temperature of 37 °C, after 36 h *Bacillus licheniformis* is inoculated, for the production of lactic acid in multiple parallel fermentation processes at a temperature of 37 °C for 48 h, after which the fermentation broth is separated from the reactor and filtered. Then, it is taken to a precipitation reactor where it is mixed with calcium hydroxide. Finally, the calcium lactate is dried at a temperature of 60°C in a convection dryer.
For glucose syrup production, ripe bananas are peeled on the conveyor belt and crushed to obtain the banana pulp. The pulp is transported to a reactor with a heating jacket and agitator where the liquefaction processes occur through alpha-amylase enzyme at a temperature of 80°C for a period of 60 minutes and enzymatic saccharification at 60 °C for 24 – 48 hours, using glucoamylase (Naranjo et al., 2014). The obtained glucose syrup is decolorized with activated charcoal at 60°C for 15 minutes. Subsequently, it passes through a 1-micron pore-size filter, and later ultrafiltration is done through a 0.001-micron membrane. Finally, the syrup is concentrated through a falling film evaporator at 70°C to a solid concentration between 60–70% w/w.

2.3 Economic and environmental assessment

Economic assessment was made using MATLAB software to calculate the economic indicators for a range of processing scales and to estimate the MPSEF using data from the simulations in Aspen Plus ®. In order to have results better adjusted to the current realities of the Colombian Caribbean region and the small scale of the processes studied, the capital costs of equipment were obtained from quotations to national companies, catalogues, and bibliographic reviews of application examples with similar characteristics. Frequently, cost estimation studies have used exponential functions in their models to scale up or down the total capital cost of the plants. However, as pointed out in Leboreiro and Hilaly (2013), the use of an exponential function is based on the assumption that all equipment in the plant scales exponentially, nevertheless, the volume of large biological reactors, such as saccharification vessels and fermenters is limited by practical constraints. The scaling capacity of bio-reactor trains in biorefineries is done by the addition of vessels rather than increasing the volume of individual vessels. As a consequence, capital required for bioreactors scales linearly with capacity while other process equipment scales exponentially. For this reason, Eq(1) proposed in Leboreiro and Hilaly (2013) is used to estimate total capital costs for equipment.

$$C_{TPEC} = k \cdot P^{\alpha} + m \cdot P \quad (1)$$

Where C_{TPEC} is the total purchased equipment cost, k and α are exponential scaling factors of equipment that scales exponentially, and m is the linear scale factor for equipment that scales linearly.
Profitability analysis was made by calculating the net present value (NPV), internal return rate (IRR), and payback period (PBP). For this, capital depreciation was applied using the straight-line method with a salvage percentage of 7%, income tax of 33%, and a discount rate for a cash flow analysis of 10% (based on the average annual interest rate in Colombian banks). The conversion value for prices in US dollars was taken in 2021 as 1 USD = 3400 Colombian pesos (COP).
The environmental analysis of each MBR conceptual design was carried out under the standardized waste reduction algorithm using the free license software WARGUI®, developed by the United States Environmental Protection Agency. This algorithm allows describing the generation of the environmental impact of a chemical process, using the information on the mass flows and composition of input and output streams of the process and also toxicological data of the substances that make up said streams (Young et al., 2000). Eight categories of environmental impact are evaluated, which are divided into four categories of global atmospheric impact: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), and Photochemical Oxidation Potential (PCOP), and four categories of global toxicological impact: Human Toxicity Potential by Ingestion (HTPI), Human Toxicity Potential by Exposure (HTPE), Aquatic Toxicity Potential (ATP), and Terrestrial Toxicity Potential (TTP).

2.4 Renewable energy integration

Solar power integration analysis was supported on the research of Tora and El-Halwagi (2010). In that study, non-linear programming models are used to calculate the contribution of solar energy in steam generation and also designed the required area of solar collectors minimizing the total annualized cost of the plant. The reader is referred to the before-mentioned paper to get a detailed explanation of the model and the procedure.
In the present work, the configuration shown in Figure 1 is proposed, where part of the heat generated by the solar collectors is used to generate electrical power through an organic Rankine cycle (ORC). This type of cycle is being already used on a commercial scale (manufactured by companies like ENOGIA and Rank) and has several advantages for its use in small-scale energy production and with relatively low-temperature sources such as parabolic solar collectors. Also, a furnace or gas-fired heater is used to account for the intermittence of solar power and to maintain a constant thermal oil temperature.
LINGO software was used to solve the non-linear programming model to calculate the monthly solar power contribution and optimal solar collector area to achieve an annual 60% of solar energy contribution in the system. Solar radiation data was taken from NASA online database at a proposed location for the MBR. Efficiency of the parabolic solar collectors was calculated with equations and parameters found in Bruno et al. (2008). The total cost of this equipment was estimated using the correlation presented in the work of Tora and El-Halwagi (2010) and adjusted with the customer price index.
Solar collectors' operations and maintenance costs were taken as 0.016 USD/kW-h as reported in International Renewable Energy Agency (2020). For ORC system technical information was taken from Enogia catalogues and economic data such as capital investment cost (2,500 €/kW) and operating costs (0.24 €ct/kW-h) from the study of Pál (2017).

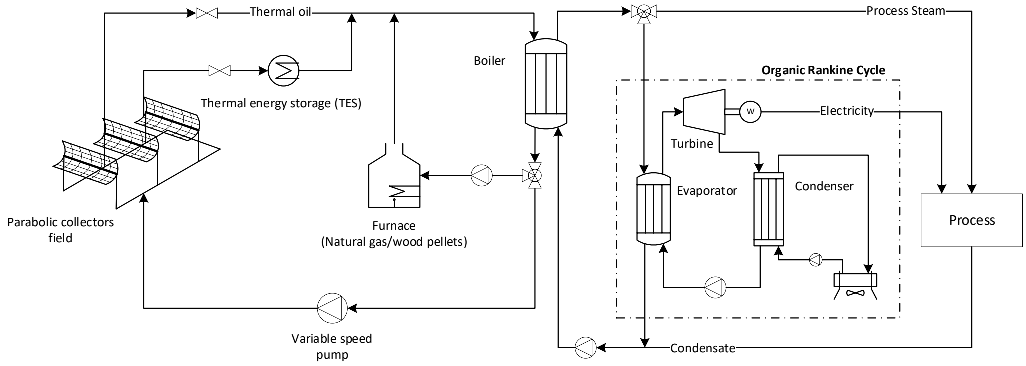

Figure 1: Conceptual diagram of proposed power system integrated to solar energy.

3. Results

3.1 Mass balance and energy requirements

For the simulation of cassava MBR, fiber fraction of biomass was considered as XYLAN and unknown dissolved solids or impurities as SOLUNKN from the work of Wooley and Putsche (1996).
Production yields obtained based on the processing of one daily ton of cassava were: 254.6 kg of cassava starch (H_2O: 8%, starch: 91.3%, fiber: 0.7%), 19.2 kg of calcium citrate (H_2O: 6%, calcium citrate: 67.9%, $Ca(OH)_2$: 1.2%, SOLUNKN: 24.9%) and 3.5 Nm^3 of biogas (CH_4: 57.33% v/v, CO_2: 42.50% v/v, H_2O: 0.06 %v/v, H_2S: 0.11% v/v). It should be noted that the calcium citrate obtained contains impurities of around 25%, this is due to the fact that technologies or purification stages such as ion exchange resins or ultrafiltration were not taken into account due to their prohibitive cost. This product, in order to be marketed to the food or pharmaceutical industries, should be purified in a centralized plant.
For rejected banana MBR, the fruit pulp was divided into equal fractions for the production of flour and glucose syrup. And the peel obtained in each of these sections was used for the production of calcium lactate. Composition of banana pulp and peel was taken from Naranjo et al. (2014).
For each processed ton of rejected bananas, the following was obtained: 127.5 kg of flour (H_2O: 6%, starch: 88.9%, fiber: 5.1%), 6.3 kg of calcium lactate (H_2O: 8%, calcium lactate: 88.4%, $Ca(OH)_2$: 3.6%) and 118 kg of glucose syrup (H_2O: 28%, glucose: 72%). The syrup is usually composed of a mixture of sugars such as dextrose, maltose, and glucose. For simplicity, in the simulator all this composition was taken as glucose.
Regarding the energy requirements, for a 10 t/day processing capacity, thermal and electrical power for cassava MBR are 5,029.8 MJ/day and 173.4 kW-h/day. And for the same scale in the rejected banana MBR these values are 10,278.4 MJ/day and 208.5 kW-h/day respectively. This difference could be explained by rejected banana MBR having more drying stages for flour and calcium lactate, as well as the evaporation step in the glucose syrup production, and also more solid handling equipment which requires more electrical power.

3.2 Economic analysis

After the profitability analysis for different scales was made, it was found that the MPSEF for cassava and rejected banana MBRs was 4.2 and 22.4 t/day respectively (Figure 2).

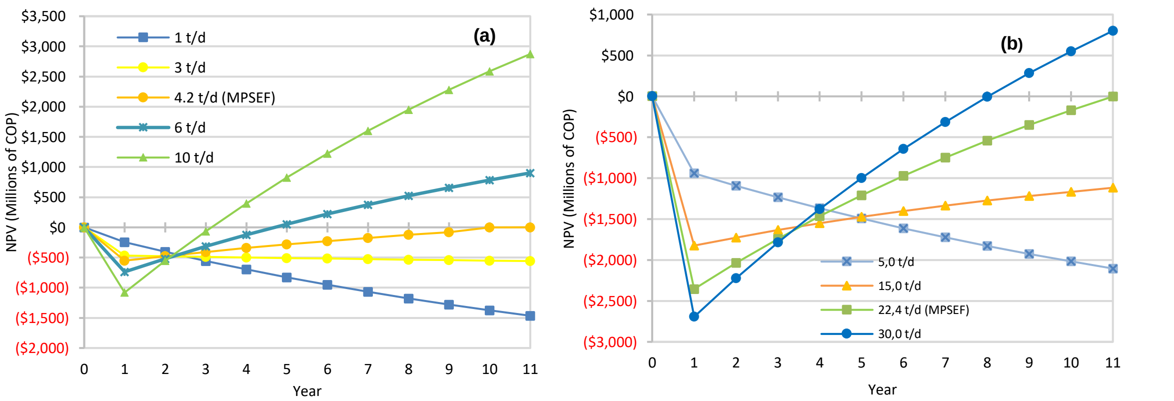

Figure 2: Cumulative discounted cash flow diagram for different processing scales in (a) Cassava MBR and (b) Rejected banana MBR.

These are scales at which the net present value becomes zero at the end of the plant's lifetime. This shows, that the cassava MBR is probably more suitable for a small-scale implementation as manufacturing costs are relatively lower than the ones in the rejected banana MBR. This could be explained by the lower complexity and energy requirements of the unit operations involved in each process, for example, utilities take 27% of manufacturing costs in rejected banana MBR versus 12% in the cassava MBR.
As for other key economic performance indicators, NPV for cassava MBR at 10 t/day was found to be $2,873,681,443 COP with an IRR of 41.3% and a payback period of 2.2 years. For rejected banana MBR, at a capacity of 30 t/day, these values were $945,742,002 COP, 6.5%, and 6.9 years, respectively.

3.3 Environmental analysis

The results of the environmental assessment of the cassava microbiorefinery process are shown in Figure 3. Natural gas was considered in WARGUI software to account for energetic requirements. The categories that contributed the most to the environmental impacts for the cassava MBR were the potential for human toxicity by ingestion (HTPI) and the potential for terrestrial toxicity (TTP). This may correspond to effluents that contain a high organic load such as of the starch extraction process. In total, this process generates an output of 0.12 PEI per kg of products. Considering the generation rate per hour at 10 t/day (base case), there is a total value of -13.1 PEI/h. For the rejected banana MBR the highest environmental impact potentials were acidification (AP) and global warming (GWP). This reflects what was previously mentioned regarding the high energy requirements of the process for a small scale since natural gas was taken into account in the WAR program as fuel. In total, the potential environmental impacts resulting from the process are 0.102 PEI per kg of product and a rate of -9.4 PEI/h at the base case. The generated PEI is calculated as the outflows minus the inflows PEI, this means that processes where this value is negative, could be environmentally sustainable, especially in projects like rejected bananas as one third of this raw material is disposed as waste.

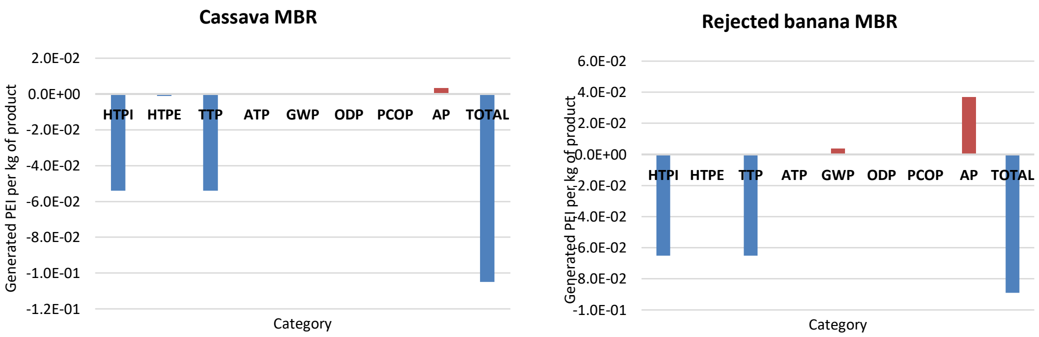

Figure 3: Environmental assessment using WAR Algorithm.

3.4 Solar power integration

For the assessment of solar power integration, cassava MBR at 10 t/day was selected as a case study. Location near municipality of Sahagun was selected (coordinates: 8.9635, -75.421) due to its large cassava annual production. Optimal opening area of solar collectors was calculated at 596.6 m^2 or 1300.6 m^2 in gross area terms, for a 60% annual solar power contribution. Solar collectors' capital cost of 240,450,200 COP and operating cost of 47,467,389 COP/year were estimated.

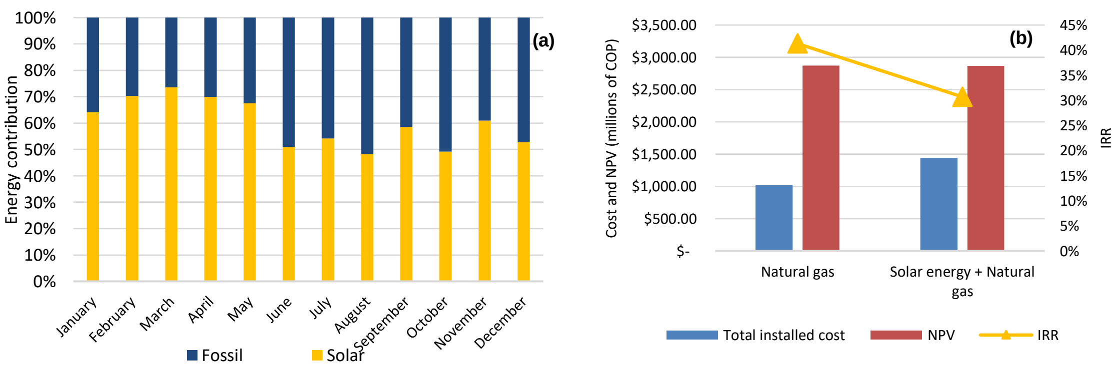

Figure 4: Monthly solar and fossil energy contributions (a) and impact of the solar-assisted power system on the economic performance in Cassava MBR at 10 t/day base case (b).

Figure 4a shows the monthly contribution of solar energy, which oscillates between 50 – 70%, as this location does not have a significant variance in solar radiation during the year. Figure 4b presents the impact on the economic performance of the integrated solar system. The total installed cost rises with the addition of solar collectors but IRR decreases 24.9%, which means that manufacturing cost savings in natural gas are not enough to increase the profitability over the lifetime of the project.

4. Conclusions

The present work proposes the conceptual design of two small-scale biorefineries based on cassava and rejected bananas in the context of the Colombian Caribbean region. These types of processes provide several benefits applied in the Colombian rural agricultural sector and could mean a contribution to solving problems such as social inequality and the economic dependence of farmers on the final sectors of the value chain. It was found that the configuration with the less complex and energy-demanding unit operations was the most suitable for small-scale, as an MPSEF of 4.2 t/day was estimated for cassava MBR versus 22.4 t/day for rejected banana MBR. The environmental evaluation gave favorable results, with generated PEI values of -13.1 and -9.36 PEI/h respectively. Regarding the integration of the MBRs to a power system assisted by solar energy and cogeneration with an ORC, it was found that the weather conditions in the municipality of Sahagun (chosen as case study for the cassava MBR) could make the use of parabolic solar collectors to provide 60% of energy requirements technically viable. However, the profitability of the plant decreases as savings in natural gas cannot compensate for the total installed cost increase.

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