Biodiesel and Hydrogen Production in a Combined Palm and Jatropha Biomass Biorefinery: Simulation, Techno-Economic, and Environmental Evaluation

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ABSTRACT: The biodiesel from lignocellulosic materials has been widely recognized as an alternative fuel to meet energy requirements worldwide, facing fossil fuel depletion, and emerging energy policies. In this work, the biorefinery approach was applied for biodiesel production from jatropha and palm oils in order to make it economically competitive by the utilization of residual biomass as the feedstock for obtaining hydrogen via steam reforming of glycerol and gasification. The linear chains for hydrogen and diesel were simulated using UniSim software and main stream properties were collected from the literature or predicted by correlations. The proposed scheme of biorefinery was analyzed through environmental and techno-economic assessment to identify the feasibility of this process to be implemented. Three different blends of oils (JO10-PO90, JO20-PO80, and JO30-PO70) were considered in the environmental analysis to determine alternatives for reducing potential environmental impacts (PEIs). It was found that the acidification potential highly contributed to the environmental impacts attributed to the use of fossil fuels for heating requirements, and JO30-PO70 blend exhibited the lowest PEI value. The economic indicators were calculated to be 8,455,147.29 $USD and 33.18% for the net present value and internal rate of return, respectively. These results revealed that the proposed combined biomass biorefinery is feasible to be scaled up without causing significant negative impacts on the environment.

1. INTRODUCTION

Recently, the development of clean energy sources has become necessary in order to meet energy demands because of the rapid population increase, massive industrialization worldwide, and environmental concerns. In addition, energy policies have encouraged the use of renewable sources to assure sustainable development and energy security. Biodiesel from lignocellulosic biomass seems to be an attractive alternative for fossil fuel substitution because of its favorable emission profiles, renewability, nontoxicity, high cetane number, and good lubricity. Several raw materials derived from forestry, agriculture, and agro-industrial wastes exhibit good properties as feedstocks for biodiesel production. Vegetable oils from palm, coconut moringa, and soybean, among others, have been widely used as alternative fuels because they do not contribute to the global carbon dioxide buildup. The transformation of these oils into biodiesel is carried out by the transesterification process using alcohol (methanol or ethanol).

The oil palm is a perennial tree that remains competitive because of the increment of the yield per unit area. The high oil content of this crop allows being used as a potential source of renewable energy. The Jatropha curcas L. is a drought-resistant crop that grows in the tropical and subtropical world. It is a poisonous, semi-evergreen shrub reaching a height up to 6 m that may cause gastrointestinal issues after human ingestion. Despite its high toxicity, oil content of the jatropha seed is about 300–400 g/kg which makes it an appropriate alternative feedstock for bioenergy production. The single biodiesel-oriented manufacturing plants are not economically competitive against oil refineries and alternative utilization paths have been investigated in order to overcome these drawbacks. The biorefinery concept represents an
alternative for the integrated use of the biodiesel industry-derived wastes generating a suite of products as hydrogen. This concept is based on biomass conversion processes to produce power, fuel, and chemicals such as biodiesel, biohydrogen, and biomethane. For example, the crude glycerol obtained during biodiesel production is used to produce gaseous fuels by steam reforming and biomass gasification. The application of biorefinery for biomass valorization offers several benefits because of the diversification in feedstocks and products while addressing sustainability goals.

The scheme of a biorefinery requires to be evaluated by different computer-aided tools such as techno-economic analysis and environmental assessment. These tools allow to assess the potential economic feasibility of bioenergy chains and understand its environmental performance. Numerous methodologies have been developed to assess the performance of chemical processes in the early conceptual design phase under a sustainability concept. Moreno-Sader et al. applied the tool for the reduction and assessment of chemical and other environmental impacts to quantify the environmental performance of palm oil production based on the emission media. Romero-Perez et al. used the techno-economic sensitivity analysis to identify operating variables that most contributed to the economic performance of palm oil biorefinery. Meramo-Hurtado et al. used the waste reduction algorithm (WAR) to determine the potential environmental impacts (PEIs) related to the industrial production of levulinic acid via acid-catalyzed dehydration.

Several works have addressed the synthesis and evaluation of biorefineries from J. curcas L. and oil palm in order to face the drawbacks of biodiesel industries using lignocellulosic materials. Table 1 summarizes recent contributions found in the literature about these feedstocks in biorefineries.

| biorefinery feedstock | environmental analysis | techno-economic analysis | references |
|-----------------------|------------------------|--------------------------|------------|
| J. curcas oil palm    | x                      | x                        | Navarro-Pineda et al. |
| J. curcas             | x                      | x                        | Batlle et al. |
| J. curcas             | x                      | x                        | Martinez-Hernandez et al. |
| J. curcas             | x                      | x                        | Vivas and Collado |
| J. curcas             | x                      | x                        | Martinez-Hernandez et al. |
| J. curcas and microalgae oil palm | x      | x                        | Garcia-Nuñez et al. |
| J. curcas and microalgae oil palm | x      | x                        | Herrera-Aristizábal et al. |

Table 1. Recent Works on J. curcas L. and Oil Palm-Based Biorefineries

The aim of this work is to apply the biorefinery concept for biodiesel production from J. curcas and palm oils and utilization of processing wastes to convert residual biomass and glycerol into hydrogen. To this end, a combined biomass biorefinery was simulated using UniSim software to obtain extended mass and energy balances. After the conceptual design and simulation, the feasibility of the process was evaluated using a techno-economic analysis tool. The PEIs were quantified via WAR under the atmospheric and toxicological categories of impacts. These assessments provided insights about the sustainability of the biodiesel production from both biomasses.

2. METHODS

The methodology followed in this work addressed the conceptual design of the combined biomass biorefinery based on the information available in the literature for these types of biomasses (J. curcas and African oil palm). The chemical composition of biomasses and main operating conditions for biomass transformation into high-value products were collected from several contributions. In this case, hydrogen and biodiesel were the products of the biorefinery. After designing the entire process, the biorefinery was simulated in UniSim software, which provided extended mass and energy balances. To validate simulation results, production yields provided by software were compared with those reported in the literature at the experimental level. These process data were entered into the computer-aided tools selected for the evaluation of economic and environmental performance of the entire biorefinery.

2.1. Process Description.

The general scheme of the combined biomass biorefinery from jatropha and palm oils is shown in Figure 1. The selected feedstocks exhibit a high content of free fatty acids (FFAs) that are transformed into biodiesel by alkaline transesterification. For African palm oil, the FFA content was 1.25% wt, while J. curcas oil accounted for 15.04% wt of FFA. The extraction of both oils generates a huge amount of lignocellulosic wastes, which can be used for producing high-value products. The proposed biorefinery involves the utilization of these lignocellulosic materials for producing hydrogen via a gasification technique. The glycerol obtained from the transesterification reaction is also considered for energy production by steam reforming. In this context, the conceptual design of the combined biorefinery includes...
four main sections: (i) biodiesel production from oils through alkaline transesterification, (ii) steam reforming of glycerol, (iii) biomass gasification, and (iv) hydrogen purification.

The process of extracting oils is not covered in this work, hence, the amount of the residual lignocellulosic material generated during oil extraction was estimated according to the information reported by Ganduglia et al.\textsuperscript{35} For jatropha, it has been reported that the fruit shells are composed of 36.3, 63.07, and 56% of husks, seeds, and oil, respectively.\textsuperscript{36} The lignocellulosic material exhibits different complex biopolymers such as cellulose, lignin, and hemicellulose, whose composition varied depending on the extraction process and plant nature. The composition of these residues after oil recovery from palm and jatropha is listed in Tables 2 and 3, respectively. The elemental analysis of both biomasses was also collected from the open literature and summarized in Table 4.

The sodium hydroxide removal from the glycerol stream was simulated in UniSim Design software assuming a capacity of 29.34% wt.\textsuperscript{40} Afterward, methanol was recovered using a distillation column and was mixed with the remaining water and traces of methanol.\textsuperscript{41} The syngas is fed into an adiabatic reactor that was required for performing water gas shift (WGS) reactions that convert CO into H\textsubscript{2}. The effect of temperature was evaluated to determine the most suitable condition for increasing the hydrogen production yield. The glycerol/water (G/W) molar ratio selected was 1:9 reducing the production of carbon monoxide as reported by Sad et al.\textsuperscript{37}

2.1.1. Steam Reforming of Glycerol. In order to simulate the production of hydrogen via steam reforming, operating conditions and properties found in the literature were considered.\textsuperscript{56} A Gibbs reactor was used for the decomposition of glycerol into carbon monoxide and hydrogen. An adiabatic reactor was also required for performing water gas shift (WGS) reactions to convert CO into H\textsubscript{2}. The effect of temperature was evaluated to determine the most suitable condition for increasing the hydrogen production yield. The glycerol/water (G/W) molar ratio selected was 1:9 reducing the production of carbon monoxide as reported by Sad et al.\textsuperscript{37}

2.1.1.2. Biomass Gasification. This process for hydrogen production was based on assumptions and operating conditions reported by many authors such as Bassouini et al.\textsuperscript{38} and Gonzalez Laguado and Quintanilla Prada.\textsuperscript{59} The empty fruit bunches (EFBs) and palm pressing fiber (PPF) were considered as useable oil palm biomass, which were simulated separately with different chemical compositions. For jatropha, the residues were de-oiled cake (DOC) and fruit without seeds (F). The gasification and WGS reactions using steam as the gasifying agent were considered and steam/biomass (S/B) mass ratio = 2 was selected according to the work carried out by Khan et al.\textsuperscript{60} The thermodynamic package recommended for these processes is Peng–Robinson and the chemical composition of feedstocks was found in many works.\textsuperscript{39–42} The operating conditions for biomass gasification are summarized in Table 7.

2.1.1.3. Hydrogen Purification. It is required to separate hydrogen from syngas components such as CO\textsubscript{2}, CO, and CH\textsubscript{4} and hence, pressure swing adsorption (PSA) technology is used for hydrogen purification. The syngas is fed into an adsorption column under high pressure to obtain hydrogen with a purity of around 98–99.99% mol.\textsuperscript{61} The simulation of this stage considers real operating conditions of a typical industrial plant. The adsorption process occurs at room temperature (25 °C) and an inlet pressure of 40 atm. The adsorption column is represented as a black box allowing to separate the stream components in the mass percentage reported by Song et al.\textsuperscript{62}

Table 2. Composition of the Lignocellulosic Residual Biomass from African Palm

| component     | EFB (% wt)\textsuperscript{37} | PPF (% wt)\textsuperscript{37} |
|---------------|-------------------------------|-------------------------------|
| cellulose     | 38.8                          | 37.2                          |
| hemicellulose | 35.64                         | 28.5                          |
| lignin        | 25.25                         | 38.7                          |

Table 3. Composition of the Lignocellulosic Residual Biomass from Jatropha

| component       | de-oiled cake (% wt)\textsuperscript{38} | fruit (% wt)\textsuperscript{38} |
|-----------------|-------------------------------------------|---------------------------------|
| cellulose       | 53.5                                      | 56.31                           |
| hemicellulose   | 16.6                                      | 17.41                           |
| lignin          | 24.9                                      | 23.91                           |
| others          | 5                                         | 2.37                            |

Table 4. Elemental Composition of Palm and J. curcas Residual Biomasses

| component | palm bagasse (%) | Jatropha bagasse (%) |
|-----------|------------------|----------------------|
| C         | 45\textsuperscript{a} | 78.20\textsuperscript{b} | 45.76\textsuperscript{c} | 45.50\textsuperscript{d} |
| H         | 6.4\textsuperscript{a} | 8.90\textsuperscript{b} | 6.30\textsuperscript{c} | 7.20\textsuperscript{d} |
| N         | 0.25\textsuperscript{a} | 3.56\textsuperscript{b} | 0.42\textsuperscript{c} | 0.4\textsuperscript{d} |
| O         | 47.3\textsuperscript{a} | 8.04\textsuperscript{b} | 47.44\textsuperscript{c} | 43.30\textsuperscript{d} |
| S         | 1.06\textsuperscript{a} | 1.3\textsuperscript{b} | 0.07\textsuperscript{d} | |

\textsuperscript{aRef 40, bRef 41, cRef 42, dRef 39}
2.2. Environmental Analysis. To assess environmentally the proposed combined biomass biorefinery, the WAR was developed. This tool describes the PEIs considering different categories of impacts divided into atmospheric and toxicological.28 The PEI output provides information related to the external environmental efficiency, which refers to the capacity of a process for obtaining final products under a minimum discharge of potential. The total output rate of PEI is calculated by eq 1, where \( i_{\text{out}}^{(t)} \), \( i_{\text{out}}^{(cp)} \), \( i_{\text{we}}^{(cp)} \), and \( i_{\text{we}}^{(ep)} \) represent the rate of PEI leaving the system due to chemical interactions, the rate of PEI out of the system due to energy generation processes, and PEI out of a system as a result of the release of waste energy due to energy generation and chemical processes, respectively.28

\[
\sum_{i=1}^{2} \left( i_{\text{out}}^{(t)} + i_{\text{out}}^{(cp)} + i_{\text{we}}^{(cp)} + i_{\text{we}}^{(ep)} \right) = 0
\]  

The effect of blend composition was evaluated by varying the contents of jatropha and palm oils in order to analyze alternatives for reducing PEIs related to feedstock conditions.

2.3. Techno-Economic Feasibility Analysis. The techno-economic feasibility analysis enables to compare both technical and economic efficiencies of many processes.64 The total capital investment (TCI) involves the funds needed to purchase and install the biodiesel manufacturing plant including equipment, facilities, and raw materials, among others. The TCI is described by eq 2, where FCI is the fixed capital investment, WCI is the working capital investment, and SUC is the start-up investment.

\[
\text{TCI} = \text{FCI} + \text{WCI} + \text{SUC}
\]  

The net cash flow (NCF) was calculated by eq 3, where AOC represents the annualized operating costs and \( \sum m_i C_i \) is the annual income.

\[
\text{NCF} = \sum m_i C_i - \text{AOC}
\]  

The economic profitability indicators selected to assess the combined biomass biorefinery are the net present value (NPV) and internal rate of return (IRR). The IRR is the interest rate at which the NPV is equal zero. The NPV is one of the most insightful profitability criteria that is calculated by eq 4, where \( \text{ACF}_n \) is the net income for the \( n \)th year.

\[
\text{NPV} = \sum_{n=1}^{\infty} \frac{\text{ACF}_n}{(1+i)^n}
\]

### Table 6. Operating Conditions for Biodiesel Production from Palm and Jatropha Oils

| Transesterification | Methanol Recovery | Glycerol Separation |
|---------------------|-------------------|---------------------|
| **Palm Oil**        |                   |                     |
| Catalyst            | NaOH              | 2                   |
| Reactor type        | CSTR              | stages              |
| Temperature (°C)    | 60                | distillate mass flow (kg/h) |
| Pressure (kPa)      | 400               | 1345                |
| MeOH/oil ratio      | 06:01             | 0.997               |
| Residence time (h)  | 1                 | neutralization (kmol/h) |
| Conversion (%)      | 99                | 0.92                |
| **J. curcas oil**   |                   |                     |
| Catalyst            | NaOH              | 2.5/4.5             |
| Reactor type        | CSTR              | stages              |
| Temperature (°C)    | 65                | distillate mass flow (kg/h) |
| Pressure (kPa)      | 400               | 2425/2245           |
| MeOH/oil ratio      | 5:1/6:1           | 0.994/0.99          |
| Residence time (h)  | 1.5/1.0           | neutralization (kmol/h) |
| Conversion (%)      | 99/99             | 0.92                |

*Ref 54. *Ref 55. *Ref 53.

### Table 7. Operating Conditions for Biomass Gasification

| Operating Condition | Bagasse | Steam | Gasification Reaction |
|---------------------|---------|-------|-----------------------|
| Temperature (°C)    | 25      | 400   | 1000                  |
| Pressure (kPa)      | 2000    | 2000  | 2000                  |

3. RESULTS AND DISCUSSIONS

3.1. Process Simulation. 3.1.1. Biodiesel Production via Transesterification of Jatropha and Palm Oils. This simulation is shown in Figure 2. As can be observed, palm...
Table 8. Feedstock Streams for Biodiesel Production

| oil blend (% wt) | jatropha oil (kg/h) | jatropha bagasse (kg/h) | palm oil (kg/h) | PPF (kg/h) | EFB (kg/h) | total bagasse (kg/h) |
|------------------|---------------------|-------------------------|----------------|------------|------------|---------------------|
| JP30-PO70        | 3300                | 6035                    | 7700           | 9411       | 14,861     | 30,307              |

Table 9. Fuel Properties from Simulation of Produced Biodiesel

| property                  | biodiesel from palm oil | biodiesel from jatropha oil | JP30-PO70 | EN 14214 |
|---------------------------|-------------------------|-----------------------------|-----------|----------|
| ester content (% wt)      | 97.74                   | 98.83                       | 96.53     | min 96.5 |
| density@15 °C (kg/m³)     | 878.65                  | 879.33                      | 878.77    | 860–900  |
| viscosity@40 °C (cSt)     | 4.34                    | 4.23                        | 4.21      | 3.5–5    |
| cetane number             | 62.15                   | 53.27                       | 58.73     | >51      |
| iodine index              | 52.29                   | 105.70                      | 66.75     | <120     |

Figure 3 shows the hydrogen process simulation by the glycerol steam reforming technique, which consists of a steam reformer (GBR-100), a WGS reactor (ERV-101), water–gas separation vessel (V-102), and molecular sieves to separate hydrogen from syngas. The system is operated at the atmospheric temperature and steam to a carbon (S/C) ratio = 3. The reformed water is heated in E-110 to obtain reformed steam, which is fed into the reformer (GBR-100) along with glycerol (GlyceM1). The products of the reforming reaction are cooled (E-111) and sent to the WGS reactor (ERV-101) that operates in an equilibrium model. The resulting syngas is separated from water in the V-102, and hydrogen is collected in the molecular sieves. Table 10 summarizes the gas production through steam reforming of jatropha oil.

Table 11 shows the in

Figure 3. Simulation flow sheet for hydrogen production through glycerol steam reforming.
obtain the syngas required to produce hydrogen. Table 12 presents the syngas composition for a blended jatropha oil−palm oil (JO30-PO70). Nipattummakul et al. 68 reported similar values for the molar composition of syngas as follows: H₂ (0.52% mol), CO (0.30% mol), CO₂ (0.14% mol), and CH₄ (0.001% mol). Li et al. 69 also obtained an approximated volumetric composition: 53.6, 20.5, 20.9, and 4.4% vol for H₂, CO, CO₂, and CH₄, respectively. The simulation results fitted the compositions obtained experimentally by other authors suggesting a good prediction for the real process.

The route for biomass gasification to hydrogen is shown in Figure 5. As can be observed, the biomasses are mixed and sent to a gasifier (GBR-100-2), in which gasification reactions took place. The biomass thermal gasification produces a gas called syngas or synthesis gas that is mainly CO and H₂ along with a minor amount of CO₂ and CH₄. 70 Then, the CO content is converted into hydrogen and carbon dioxide via WGS in adiabatic reactors at thermodynamical equilibrium (ERV-100, ERV-101-2, ERV-102) and the resulting gas is feed into a separation vessel (V-100) to remove condensates from the syngas stream. Afterward, this stream is compressed and sent to a PSA unit (X-100-2). Table 13 presents the composition of the main inlet and outlet streams involved in hydrogen production through biomass gasification.

### 3.2. Global Energy Balance of the Biorefinery.

The global energy balance around the combined palm and jatropha biorefinery was performed in order to calculate the net energy gain of the system. As shown in Figure 6, caloric content of biomasses and oils were considered for the calculation of energy inputs. The utilities were estimated with the process simulation at 2987.99 kW. The energy output included biodiesel (JP30-PO70) and hydrogen from both reforming and gasification. The higher heating value (HHV) of oil palm biomasses as well as jatropha bagasse were found in the literature. 71,72 The HHV of jatropha and palm oils were simulated properties provided by software. The net energy ratio (NER) was calculated as the ratio between the net energy output and net energy input. A value of NER > 1 indicates that the fuel system has a net energy gain, that is, the energy given for the production of biodiesel and hydrogen is higher than the energy obtained in the use of biodiesel and hydrogen.

Table 10. Composition of Main Streams for Glycerol Steam Reforming

| properties       | reformed steam | glycerol/water | water | H₂ | gas |
|------------------|----------------|----------------|-------|----|-----|
| temperature (°C) | 200            | 200            | 100   | 100| 126 |
| pressure (kPa)   | 101.3          | 101.3          | 4053  | 3881| 3881|
| molar flow (kmol/h) | 55.02         | 69.16          | 71.88 | 84.3958| 41.44|
| mass flow (kg/h) | 991.35         | 2166.10        | 1298.23| 170.40| 1688.82|
| composition (wt) | H₂ 0.0000      | 0.0000         | 0.0000| 0.9983| 0.0006|
|                  | CO 0.0000      | 0.0000         | 0.0000| 0.0000| 0.0000|
|                  | CO₂ 0.0000     | 0.0000         | 0.0045| 0.0000| 0.9532|
|                  | CH₄ 0.0000     | 0.0000         | 0.0000| 0.0000| 0.00047|
|                  | C₂H₆ 0.0000    | 0.0000         | 0.0000| 0.0000| 0.0000|
|                  | H₂O 0.0000     | 0.4720         | 0.9955| 0.0016| 0.0406|
|                  | glycerol 0.0000| 0.5280         | 0.0000| 0.0000| 0.0000|

Figure 4. Effect of temperature on hydrogen production through steam reforming.

Table 11. Production Yield of Gases Using Steam Reforming Technique

| production yield (gas/glycerol, mass ratio) | H₂ | CO₂ | CO | CH₄ |
|---------------------------------------------|----|-----|----|-----|
| simulation                                  | 0.130 | 1.001 | 0.263 | 0.0069 |
| experimental 56                             | 0.149 | 1.334 | 0.162 | 0.0000 |

Table 12. Syngas Composition Produced through Biomass Gasification

| components | composition (% mol) | composition (% vol) |
|------------|---------------------|---------------------|
| H₂         | 0.596               | 49.82               |
| CO         | 0.228               | 23.09               |
| CO₂        | 0.174               | 26.92               |
| CH₄        | 0.001               | 0.16                |

Palm oil (JP30-PO70). Nipattummakul et al. 68 reported similar values for the molar composition of syngas as follows: H₂ (0.52% mol), CO (0.30% mol), CO₂ (0.14% mol), and CH₄ (0.001% mol). Li et al. 69 also obtained an approximated volumetric composition: 53.6, 20.5, 20.9, and 4.4% vol for H₂, CO, CO₂, and CH₄, respectively. The simulation results fitted the compositions obtained experimentally by other authors suggesting a good prediction for the real process.

Obtain the syngas required to produce hydrogen. Table 12 presents the syngas composition for a blended jatropha oil−palm oil (JO30-PO70). Nipattummakul et al. 68 reported similar values for the molar composition of syngas as follows: H₂ (0.52% mol), CO (0.30% mol), CO₂ (0.14% mol), and CH₄ (0.001% mol). Li et al. 69 also obtained an approximated volumetric composition: 53.6, 20.5, 20.9, and 4.4% vol for H₂, CO, CO₂, and CH₄, respectively. The simulation results fitted the compositions obtained experimentally by other authors suggesting a good prediction for the real process.

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3.3. Environmental Analysis. The PEIs of the processes involved in combined biomass biorefinery were determined by the WAR algorithm. The PEI categories considered in this work were based on the results reported by Young and
Cabezas\cite{73} as follows: human toxicity potential by ingestion, human toxicity potential by exposure, aquatic toxicity potential (ATP), terrestrial toxicity potential, global warming potential (GWP), ozone depletion potential, smog formation potential, and acidification potential (AP). Figure 7 shows the PEI for three different blends (JO10-PO90, JO20-PO80, and JO30-PO70), palm oil, and \textit{J. curcas} oil. As can be observed, the AP most contributes to environmental impacts, followed by ATP and GWP categories. These results can be attributed to the consumption of fossil fuels in order to supply the heating energy requirements for steam reforming and biomass gasification of residual lignocellulosic materials. Palm oil exhibited the highest value for AP and ATP categories, which could be assigned to the sulfur content in palm bagasse (0.029 wt) producing acids over the process. The JO30-PO70 blend generated lower PEIs (1100 PEI/h) than other blends. Hence, it was expected that the blend with a lower palm oil amount showed lower environmental impacts.

### 3.4. Techno-Economic Feasibility Analysis

The equipment costs were calculated according to the characteristic dimensions provided by simulation software. However, the hydrogen purification stage was dimensioned according to the recommendations found in the literature related to the use of three packed-bed adsorption columns.\cite{74} The cost estimation was performed through several plots reported by Peters and Timmerhaus,\cite{75} which were updated with the CEPSI index. Table 14 summarizes the total cost of equipment used for operating the biorefinery.

#### Table 13. Composition of Main Streams for Biomass Gasification

| properties     | EFB         | PPF         | Jatropha bagasse | H$_2$O bagasse | condensates | liquid wastes | hydrogen | gases |
|----------------|-------------|-------------|------------------|----------------|-------------|---------------|----------|-------|
| temperature (°C) | 20          | 20          | 20               | 25             | 25          | 150           | 25       | 46.04 |
| pressure (kPa)  | 2000        | 2000        | 2000             | 2000           | 4053        | 2000          | 3881     | 3881  |
| molar flow (kmol/h) | 1252.43     | 793.14      | 509.26           | 2169.16        | 1185.91     | 786.53        | 2315.76  | 1157.55 |
| mass flow (kg/h) | 14,860.7    | 9411.11     | 6034.56          | 39,077.65      | 21,535.23   | 14,181.30     | 4668.87  | 50,099.31 |
| composition (wt) |             |             |                  |                |             |               |          |       |
| H$_2$          | 0.064       | 0.089       | 0.063            | 0.000          | 0.0000      | 0.0000        | 1.000    | 0.001 |
| O$_2$          | 0.469       | 0.080       | 0.475            | 0.000          | 0.0000      | 0.0000        | 0.000    | 0.000 |
| C              | 0.449       | 0.782       | 0.458            | 0.000          | 0.0000      | 0.0000        | 0.000    | 0.000 |
| N$_2$          | 0.002       | 0.035       | 0.004            | 0.000          | 0.0000      | 0.0000        | 0.000    | 0.000 |
| H$_2$O         | 0.000       | 0.000       | 0.000            | 1.000          | 0.9865      | 0.9983        | 0.9983   | 0.001 |
| CO             | 0.000       | 0.000       | 0.000            | 0.000          | 0.0000      | 0.0000        | 0.000    | 0.000 |
| CO$_2$         | 0.000       | 0.000       | 0.000            | 0.000          | 0.0135      | 0.0017        | 0.0017   | 0.000 |
| CH$_4$         | 0.000       | 0.000       | 0.000            | 0.000          | 0.0000      | 0.0000        | 0.000    | 0.000 |
| S              | 0.016       | 0.013       | 0.000            | 0.000          | 0.0000      | 0.0000        | 0.000    | 0.000 |

Figure 5. Simulation flow sheet for hydrogen production via biomass gasification.

Figure 6. Energy balance of the biorefinery.
As is listed in Table 15, the raw material costs considered the inflation per year in Colombia and involved the cultivation and oil extraction costs. The selling price for different products obtained in this biorefinery were collected from Han et al.75 and are summarized in Table 16.

The fixed capital investment and working capital were calculated assuming product sale for one month. The TCI refers to funds invested to begin a product manufacture for at least one month. The proposed combined biomass biorefinery reported a FCI of 12,715,397.16 $USD, WC of 2,050,423.75 $USD, and TCI of 14,765,820.91 $USD. The total operating cost estimation was performed based on annualized raw material costs, utility costs, administrative expenses, and labor, among others. This information was useful to calculate the cash flow of over a year, which is defined as the difference between incomes and expenses. The total operating cost, sales revenue, and NCF were calculated to be 82,760,321.68 $USD, 87,726,871.58 $USD, and 4,966,549.90 $USD, respectively. The techno-economic feasibility of combined biomass biorefinery was analyzed by economic indicators (NPV and IRR) for a useful life of 15 years and annual interest rate of 20%. The economic indicators were calculated to be 8,455,147.29 $USD and 33.18% for NPV and IRR, respectively. These results revealed that the proposed combined biomass biorefinery is feasible to be implemented. In addition, similar values for IRR were obtained in other works using lignocellulosic materials.76,77

4. CONCLUSIONS

This work was focused on applying the biorefinery concept to the biodiesel production from J. curcas and palm oils with the aim of taking advantage of biodiesel industry-derived residues to generate high-value products such as hydrogen. The process simulation of linear chains provided information concerning process streams (temperature, pressure, mass flow, and composition), which were required for performing environmental and techno-economic analyses. The residual biomass conversion into hydrogen was carried out through gasification, which is one of the most used thermochemical technology. The glycerol produced as a co-product in the transesterification reaction was used in steam reforming for hydrogen production. The incorporation of these linear chains into the biodiesel production process was expected to be an alternative for making it more economically competitive. The environmental analysis results revealed that AP most contributes to environmental impacts, followed by ATP and GWP categories. The AP category also shown to be significantly high for a single biomass biorefinery reported in previous works such as oil palm-based biorefinery,28 which suggests similar environmental performance of the combined biomass design in this impact category. The blend JO30-PO70 exhibited the lowest PEIs; hence, it was selected for further studies. The NPV and IRR indicators were calculated to be 8,455,147.29 $USD and 33.18%, respectively, suggesting the feasibility of the proposed combined biomass biorefinery. The combination of both jatropha and palm oils for biodiesel production was shown to be an attractive techno-economic alternative, supporting the study performed by Sarin et al.49

The main drawback of this biorefinery design was the high
energetic demand for transforming both biomasses into valuable products. Hence, the application of process integration techniques to the simulated biorefinery is recommended in order to reduce the consumption of energy during preheating for the transesterification reaction and biomass gasification. Besides, the process safety evaluation of this design features a key aspect to be considered in future studies to assess the viability of the biorefinery in terms of fire and explosion hazards.

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Notes

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