Analysis of the feasibility of biodiesel plants through the *in situ* use of the solid residues for energy and chemicals

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Abstract

The use of non-renewable fuels such as diesel to meet the energy needs, both of industry and the transport sector, is a matter of concern due to the serious environmental impacts related to the consumption of these products. The use of renewable resources for the production of biofuels is an important alternative to mitigate the environmental impact caused by fossil fuels. In this sense, this work presents the analysis of the viability of biodiesel production, through the use of different raw materials and the exploitation of lignocellulosic residues. Four scenarios were evaluated technically and economically. Scenario 1 is based on the biodiesel production from palm oil. Scenario 2 employs jatropha oil as feedstock for the production of this biofuel. Scenario 3, in addition to the biodiesel production from palm oil, uses oil palm frond for the production of ethanol and furfural. Finally, in Scenario 4, biodiesel from jatropha oil is obtained simultaneously with furfural and ethanol from pericarp.

As a result, it was shown that Scenario 3 presents the highest economic margins. The production of biodiesel was 44.63%, while the production of ethanol and furfural from oil palm frond was 9.16%. It was evidenced that the use of lignocellulosic raw materials can offer alternatives of economic improvement to the biodiesel production. However, it depends on the cellulose and hemicellulose contents present in the residue, and the cost of pretreatment thereof.

Keywords: Biodiesel, Jatropha Curcas, Oil Palm, Waste Valorization.

1. Introduction

Currently, there is a constant concern for the availability of energy to meet the needs of the world market as we know it [1]. It is estimated that the amount of energy needed for the growth of various economies such as India and China will increase global energy consumption in the coming decades [2]. In addition, activities such as transport and industrial growth are decisive factors in the demand and availability of energy in a near future. It is calculated that 97% of the fuels used in the transport sector are of fossil origin, which shows the great dependence on oil in this sector and on the global economy [3]. However, several social and environmental problems are related to the excessive use of oil. For the environmental aspect, the generation of greenhouse gases such as carbon dioxide and others (NOx and SOx) from fossil fuel combustion are direct contributors to global warming [4]. In the same way, the political instability of countries with reserves of this resource is a social aspect to take into account.

In this sense, finding alternatives to meet energy needs without compromising the resources of future generations is a goal that has been set by academic community, industry and some governmental organizations [5], [6]. To fulfill this purpose, researchers have focused on the production and development of energy resources from renewable raw materials [7]. Biotechnology has been a key pillar in the development and production of biofuels that potentially can replace the petroleum derived fuels, boosting the idea of a biomass-based economy [8]. A clear example of the positioning of the biotechnology industry in today's economy are the production of ethanol and biodiesel. These biofuels have been projected as potentially replacing petroleum-based fuels, due to advantages as low environmental impact, high profit margins and rural development [9].

Some countries like United States, Brazil and Colombia, to name a few, have encouraged the production of these biofuels through subsidies, so that part of the producing cost is assumed by governments [10]. Another measure adopted by a large number of countries is the 80:20 blend, which refers to feed internal combustion engines with 80% fossil fuel and 20% renewable fuel [4], [11]. Although this measures have been effective and have allowed the production of both ethanol and biodiesel to be economically viable, it is expected that in the coming years with the decrease of subsidies by governments, these products will have difficulty to compete with fuels derived from petroleum [10].

Biodiesel has taken great position in the fuel market, since it can be used with minimal or no modification in diesel engines, with similar efficiency [12]. Another important feature is the low pollution that this biofuel produces compared to diesel from petroleum [13]. Regarding the social aspect, the use of biomass for the production of biodiesel implies the incorporation of rural communities in the supply chain, generating a large number of jobs and consequently increasing the purchasing power of these communities [11]. For its advantages, some authors report that by year 2035 biodiesel will replace approximately 30% of petrochemical diesel [3]. However, although biodiesel production is economically sustainable from some raw materials, it is not certain that this scenario will remain constant in future years, since the use of new oil extraction technologies such as fracking has increased the offer of oil, reducing the cost of diesel [14].

Considering the challenges that biodiesel production must face in the future, the research has focused on improving the characteristics of the production process, so that biodiesel could be obtained with good quality and low cost [15]. Consequently, the use of new methodologies as supercritical fluids for the production of biodiesel has been reported [16]. In addition, the use of different alcohols and catalysts to generate better yields and lower costs in the transesterification process has also been subject of study [13]. Although each of these researches has meant a significant advance in the development and improvement of the biodiesel production process, the economic benefits are not high enough to ensure the economic sustainability of this product in the future. However, some studies report that economic viability of biodiesel production in the future is related to the use of low cost raw materials, since the cost of the raw material is the most influential factor in the overall cost of production of this biofuel [17].

Biodiesel can be obtained from a large number of raw materials ranging from edible crops to microalgae. Each of these raw materials is divided into groups according to their characteristics. These groups are called generations [18]. The feedstocks denominated of the first generation are those crops that are used for human consumption. Some first generation feedstocks involved in the production of biodiesel are sunflower, soybean, oil palm, canola, and peanut, among others [18]. It is estimated that 95% of biodiesel is produced from first generation feedstocks [4]. The second generation feedstocks are those products that are obtained as waste from a chemical, agro-industrial or food process. The most representative of second generation feedstocks for biodiesel production is waste cooking oil [19]. Additionally, it is called third generation feedstocks to algae [20]. Fourth generation feedstocks are those oils that are not related to human consumption such as jatropha, castor and karanja [12]. Each one of the generation feedstocks gives specific characteristics to biodiesel production in the economic, environmental and social aspect.

In this sense, this paper presents an analysis of the economic viability of biodiesel production, for which four scenarios are proposed. Scenario 1 is based on the production of biodiesel from palm oil, while the Scenario 2 uses oil from jatropha curcas as raw material. Scenario 3 refers to the use of oil fronds, a lignocellulosic residue obtained from the renewal of oil palm crops, to produce ethanol and furfural coupled to the biodiesel production from palm oil. Finally, Scenario 4 employs the pericarp for the production of ethanol and furfural in parallel with the production of biodiesel from jatropha oil.

2. Methodology

2.1. Feedstocks

2.1.1. Jatropha Curcas

Jatropha oil has been studied for the production of different products like biodiesel, lubricants, biopesticides, and cosmetics, among others [21]. The use of jatropha for biodiesel production has great advantages, since this crop can be adapted to arid lands with low amount of nutrients and water [22]. This feature allows the exploitation of arid lands without enter in conflict with food security. It has been reported that jatropha oil has good characteristics in terms of its composition of fatty acids to subsequent conversion to biodiesel [21]. However, the high cost of extracting this oil is a major disadvantage [21]. In the oil extraction process, a lignocellulosic material called pericarp is obtained as residue [23]. Due to its content of cellulose and hemicellulose, it is considered as an interesting raw material for the production of platform products such as C5-C6 sugars, which will subsequently be transformed into added-value products [23].

2.1.2. Oil palm

Oil palm is one of the most cultivated crops in tropical countries, due to its high productivity per hectare and the wide portfolio of products that can be obtained from the oil of this plant [21]. Palm oil is used with food purposes in the production of oleins and stearins for bakery, in addition to its use in the production of soap [11]. It is also known that a large percentage of this oil is destined to the production of biodiesel. The production of biodiesel from oil palm has advantages such as low greenhouse gas emissions, compared with oil derived diesel [11]. However, disadvantages such as competition with food security and the production of a large number of lignocellulosic wastes that are not adequately treated, have been the subject of discussion [24]. Oil palm fronds are the most abundant lignocellulosic residue obtained in the pruning of oil palm trees for their renewal [25]. Due to its high availability and high concentration of cellulose and hemicellulose, it has become an attractive feedstocks [25]. **Table 1** shows the chemical composition of the lignocellulosic residues (oil palm fronds and pericarp), as well as the fatty acid concentration of the oil palm and jatropha oils used in this work.

Table 1. Composition of feedstocks and fatty acids

Chemical Composition (mass percentage %)		
Component	**Oil palm fronds[a]**	**Pericarp[b]**
Cellulose	42.8	36.5
Hemicellulose	14.8	12.2
Lignin	19.7	26.8
Ashes	5.8	8.7
Protein	N.D	15.8
Extractives	16.9	N.D
Fatty acids (mass percentage %)		
Fatty acid	**Palm oil[c]**	**Jatropha oil[c]**
Oleic	46.08	42.35
Linoleic	35.15	9.74
Palmitic	13.37	43.58
Stearic	5.88	4.30

[a] Data from: [26], [b] Data from: [23], [c] Data from: [4], [d] Data from: [22]. N.D: Non-determined

2.2. Processes description

2.2.1. Biodiesel

The production of biodiesel is carried out by means of sequential stages. First, a pre-transesterification reaction is performed to remove free fatty acids. The pretreated stream is then sent to a transesterification reaction with ethanol and sodium hydroxide as catalyst. The reaction is performed at 60 °C according to the kinetics described by Bambase *et* al. [27]. Subsequently, ethanol that does not react is recovered by vacuum distillation, and a decanter is used to separate biodiesel and glycerin. Finally, biodiesel is purified by removing excess alcohol and catalyst, while salts and formed soap are neutralized.

2.2.2. Sugar extraction

The lignocellulosic material, in this case pericarp and oil palm fronds, is subjected to a series of pretreatment stages. In the first stage, a reduction of size and subsequent sieving is carried out. Then, the fraction of hemicellulose present in the material is hydrolyzed to pentose with the addition of sulfuric acid 2 % w/w. This acid pretreatment was carried out in a stirred tank at 100 °C according to the kinetics reported by Jin et al. (2011) [28]. As a result of this process, a liquor rich in pentoses is generated, which is separated by a filtration system of the solid fraction that contains cellulose and lignin. The stream rich in lignin and cellulose is sent to an enzymatic hydrolysis process, where a high concentration of hexose and lignin as solid residue are obtained. This enzymatic hydrolysis is performed at 35 °C as reported by Morales-Rodriguez et al. (2011) [29]. Finally, a detoxification step is carried out to remove furfural and hydroxymethylfurfural (HMF), which was generated in acid pretreatment and could cause inhibition in the subsequent fermentative process [30].

2.2.3. Ethanol

The stream rich in hexose from the pretreatment process is subjected to a sterilization step at 121 °C to neutralize the possible biological activity. The sterilized broth is inoculated with *saccharomyces cerevisiae* at a temperature of 37 °C as reported by Rivera et al. (2006) [31]. From the fermentation stage an outflow with a concentration of about 5-10 % w/w in ethanol and some amount of biomass is obtained. Biomass is removed by means of a simple gravitational sedimentation technology. The biomass free broth is sent to a two distillation column system where the ethanol is concentrated. The first distillation column reduces the large amount of water present in the stream and concentrates the ethanol to about 45-50% w/w. The liquor is sent to a second distillation column where an ethanol concentration of about 96% w/w (azeotropic point) is obtained. Finally, a series of molecular sieves is used to concentrate the ethanol to 99.6% w/w (dehydrated ethanol).

2.2.4. Furfural

The stream rich in pentoses is sent to a dehydration process, catalyzed by hafnium pillared clays. As the reaction develops, air is fed as stripping agent. The dehydration reaction is carried out at a temperature of 170 ° C and a pressure of 10 bar. The conversion was 86.2% as reported by Cortés et al., 2013 [32] . The liquor is depressurized and the liquid fraction is recovered. Subsequently, a decantation system is used to separate the furfural, where the stream with a high concentration of furfural is sent to a system of distillation columns. The distilled furfural is recovered by bottoms, while the excess water from the dehydration is removed on the top. The separation of this component was carried out as described by Nhien et al., 2017 [33].

2.3. Scenarios description

To determine the economic viability of biodiesel production through different raw materials and the use of solid waste, four scenarios were proposed. Scenario 1 considers the production of biodiesel from palm oil through a transesterification reaction with ethanol and catalyzed by sodium hydroxide. The scenario 2 presents the production of biodiesel from jatropha oil, a fourth generation raw material. Scenario 2 is carried out under the same reaction conditions as Scenario 1. In the first two mentioned scenarios, the extraction of the oil is not taken into account.

Scenario 3 is based on the use of a lignocellulosic residue such as oil palm fronds for the production of ethanol and furfural, simultaneously with the production of biodiesel from palm oil. Finally in the Scenario 4, the production of biodiesel from jatropha oil is added to the production of furfural and ethanol from jatropha pericarp. The feed flow for the four scenarios was 1000 kg/h. Table 2 presents raw materials, technologies and products of each of the scenarios.

Table 2. Scenarios description

Scenario	Raw material	Transformation technology	Product
Scenario 1	Palm oil	Transesterification with ethanol (1:3 molar relation), catalyzed with NaOH	Biodiesel

Scenario 2	Jatropha oil	Transesterification with ethanol (1:3 molar relation, catalyzed with NaOH	Biodiesel
Scenario 3	Palm oil and oil palm fronds	Transesterification with ethanol (1:3 molar relation), catalyzed with NaOH. Fermentation with *saccharomyces cerevisiae*. Dehydration of xylose with sulfuric acid.	Biodiesel, furfural, ethanol
Scenario 4	Jatropha oil, pericarp	Transesterification with ethanol (1:3 molar relation), catalyzed with NaOH. Fermentation with *saccharomyces cerevisiae*. Dehydration of xylose with sulfuric acid.	Biodiesel, furfural, ethanol

2.4. Simulation processes

Each of the technological schemes were simulated using the commercial package Aspen plus (Aspen Technology, Inc., USA), in order to obtain mass and energy balance needed to carry out the technical and economic analysis of the different scenarios. Each of the simulated processes were subjected to a series of sensitivity analysis to find the best operating conditions. The specialized package Matlab was used to perform mathematical calculations, necessary for the kinetic modeling of the reactions performed in each of the scenarios. The thermodynamic properties for the conventional molecules were obtained from NIST database. The thermodynamic models used for the simulation were UNIFAC Dortmund and Soave Redlich Kwong with Boston Mathias (RKS-BM) Modified method for liquid and vapor phases, respectively. On the other hand, for the simulations involving ethanol, NRTL model was used. Estimates of energy consumption were made with mass and energy balances generated by the simulator Aspen Plus. With the simulator, the thermal energy required by heat exchangers and the electrical energy needs of the pumps, compressors, mills and other equipment was calculated.

2.5. Economic analysis

Capital and operating costs were calculated using Aspen Economic Analyzer (Aspen Technologies, Inc.). Specific parameters relating to Colombian conditions such as income tax rate (17%), interest rate (33%) and labor salaries, among others, were incorporated in order to calculate the production costs per unit of mass for the four scenarios [11]. This analysis was estimated in US dollars for a period of 10 years and the straight line depreciation method was used for the amortization. The Table 3 presents the prices of raw materials, products and utilities needed in the processes.

Table 3. Price/cost of raw materials, products and utilities.

Item	Unit	Price
Palm oil [a]	USD/Kg	0.032
Jatropha oil [a]	USD/Kg	0.177
Oil palm Fronds	USD/Ton	15
Pericarp	USD/Ton	25

Sulfuric acid [b]	USD/Kg	0.094
Biodiesel [b]	USD/Kg	1.52
Sodium hydroxide [b]	USD/Kg	0.635
Ethanol [b]	USD/Kg	1.07
Furfural [c]	USD/Kg	1.5
Low pressure steam [b]	USD/Ton	1.57
Medium pressure steam [b]	USD/Ton	8.18
Fuel [b]	USD/ Megawatt	24.58
Electricity [b]	USD/kWh	0.14
Water [b]	USD/m^3	0.74
Operator labor [b]	USD/h	1.84
Supervisor labor [b]	USD/h	2.76
Tax rate [d]	%	33
Interest rate [d]	%	17

[a] Data from: [34], [b] Data from: [20], [c] Data from: [35], [d] Data from: [11],

3. Results and discussion

It was possible to determine that biodiesel produced from oil palm presents higher profit margins (44.63%), with respect to the production of biodiesel from jatropha oil (24.37%). This difference in the profit margins is due to the fact that jatropha oil has a higher price compared to palm oil, which increases the overall costs of scenario 2. On the other hand, the costs obtained for biodiesel production from palm oil and jatropha, are higher than those reported by Quintero et al. (2012) [34]. However, this difference lies in the increase in reagent prices in recent years, so it is reasonable that this work present superior cost for biodiesel production than works reported years ago. It is also important to note that although the scenario 1 presents better economic margins, in recent years the importance of replacing the use of palm oil has been emphasized, due to problems such as competition with food security, land use change, loss of habitat, fragmentation of forests and adequate treatment of wastes.

Although the scenario 2 does not present a high profit margin at the moment, it should not be discarded since, the possible technification of jatropha crops and development of more efficient oil extraction technologies, would significantly improve the economic benefits of biodiesel production from this raw material. The use of jatropha oil as a raw material for the production of biodiesel is related to the rural development, since this crop can be cultivated in lands with low concentration of nutrients and minimum availability of water. This creates an opportunity of economic exploitation for farmers with arid lands, improving the quality of life of these communities. Additionally, it was established that the higher cost associated with the production of biodiesel is related to the cost of the raw material, being consistent with the results obtained by Mata et al. (2010) [17]. Table 4 presents the cost distribution of both scenario 1 and scenario 2.

Table 4. Production costs of scenario 1 and 2.

Item	Scenario 1	Scenario 2
Total raw material cost (USD/year)	3,909.464	5,832.590
Total utilities cost (USD/year)	1,427.188	1,427.188
Operation labor cost (USD/year)	36.800	36.800
Operating charges (USD/year)	9.200	9.200
Maintenance cost (USD/year)	1.760	1.760
Plant overhead (USD/year)	19.280	19.280
General and administrative cost (USD/year)	413.228	471.970
Capital depreciation (USD/year)	10.1080	101.080
Total production cost (USD/year)	5,918.000	7,899.868
Biodiesel production cost (USD/Kg)	0.841	1.149

Profit margin (USD/year)	44.63	24.37

For the scenario 3, it can be seen in Table 5 that the profit margin of the furfural and ethanol production with the use of oil palm fronds as raw material was 9.164%, which implies that this process has low profit margin but positive. However, in order for the scenario 3 to be a real option for the future economic improvement of the production of biodiesel from palm oil, the profit margin of ethanol and furfural production, should increase considerably. It can also be clearly seen in Table 5 that ethanol is obtained at a cost ($ 1.21USD/ Kg) higher than the market sale price ($ 1.07 USD/Kg). This implies that in order to improve the economic viability of the scenario 3, the process needs important improvements. One of the possibilities to be explored in the future is the use of a continuous process, membrane reactors, or the implementation of less costly separation systems. Another proposal to be considered in the next future is to replace the ethanol production by products such as butanol, ethanol and acetone through ABE fermentation, or the production of acetic acid and other organic acids of high added-value that can be obtained through hexose transformation. The Table 5 presents the cost distribution of both scenario 3 and scenario 4.

Table 4. Production costs of scenario 3 and 4.

	Scenario 3		Scenario 4	
Item	Biodiesel production	Furfural and ethanol production	Biodiesel production	Furfural and ethanol production
Total raw material cost (USD/year)	3,909.464	922.777	5,832.590	1,002.777
Total utilities cost (USD/year)	1,427.188	87.6910	1,427.188	87.6910
Operation labor cost (USD/year)	36.800	36.960	36.800	36.960
Operating charges (USD/year)	9.200	9.240	9200	9.240
Maintenance cost (USD/year)	1.760	1.760	1760	1.760
Plant overhead (USD/year)	19.280	19.360	19280	19.360
General and administrative cost (USD/year)	413.228	116.851	471970	123.251
Capital depreciation (USD/year)	101.080	101.080	101080	101.080
Total production cost (USD/year)	5,918.000	2,084.938	7,899.868	2,171.338
Biodiesel production cost (USD/Kg)	0.84		1.14	
Ethanol production cost (USD/Kg)		1.21		1.54
Furfural production cost (USD/Kg)		1.11		1.34
Profit margin	44.63	9.164	24.37	-12.42

In contrast to the economic margin reported for the scenario 3, the scenario 4 presents economic disadvantages, since the overall economic margin for the production of ethanol and furfural from pericarp was negative (-12.42 %). This negative economic margin is due to the fact that the ethanol production cost (1,543 USD/Kg) is well above the sales price of this product (1.07 USD/Kg). The high cost of production, is related with low amount of cellulose and hemicellulose content in the pericarp, compared to other lignocellulosic residues such as oil palm fronds. This means that the amount of hexoses and pentoses from the pretreatment stage is low, which implies lower product flows, but with high operational and raw material costs. For this reason it is interesting that in future studies other lignocellulosic residues from the extraction of jatropha oil will be analyzed, in order to provide alternatives for economic improvement of biodiesel production from jatropha oil.

However, because the prices of raw material, operating costs and others related to the operation of the plant are constantly fluctuating, it is essential to carry out a cost analysis to the proposed designs. In this sense, a simple sensitivity analysis was performed at the cost of the raw materials of both scenario 1 and scenario 2. As a result, it was shown that at a price of 1 USD/kg of palm oil, the profit margin of the scenario 1 is -27.81%. Likewise, in a hypothetical case where jatropha oil would have a price of 1 USD/kg, the scenario 2 would present a profit margin of -38.66 %. This negative profit margins show that the production of biodiesel is very sensitive to the change in the prices of raw materials, which implies that a process that is viable in the future should look for alternatives of economic improvements in raw materials.

4. Conclusions

The integration of solid residues into the biodiesel industry can make an interesting option. However the feasibility analysis based on mass and energy balances for the specific residues and technologies is needed to take a decision about the investments into these innovative proposals. In this case when oil palm is the raw material, it was demonstrated preliminary that in addition to the biodiesel production from palm oil, oil palm fronds can be used economically for the production of ethanol and furfural.

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