**Technoeconomic analysis of *Jatropha Curcas* integral valorization**

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**Abstract:** In this paper, the technoeconomical assessment of a Jatropha Curcas plant was conducted, taking into account three different raw materials from Jatropha Curcas in a integral valorization process: the crude oil, the seed shell and the de-oiled seed cake. This way, all the solid waste produced after the extraction process could be pelletized and exploited in the own biodiesel plant generating electricity which highly improves the overall process economically and environmentally. In addition, the crude oil can be transformed to biodiesel through a simultaneous esterification-transesterification of the free fatty acids and the triglycerides mixture using bioethanol with a 5% of water content and heterogeneous catalyst.

The economic sensitivity analysis was carried out using two different parameters which determine the profitability of the process: the internal rate of return (IRR) and the payback time. On one hand, the variables which have the highest impact over the process is the electricity price because is the main source of revenues in the plant and on the other hand, the variable with the lowest impact over the process is the bioethanol price because of the high ratio proposed (20:1) and over 80% of this alcohol is recycled at the beginning of the process.

**Keywords:** Transesterification; Jatropha, Biodiesel, Simulation, Pellet, Glycerol

1. **Introduction**

Nowadays, electricity supply is one of the main factors to determine the development of a nation. The consumption of electricity keeps growing due to the population rise and the growth of developing countries[1,2]. The widespread use of energy has contributed to environmental damage related to climate change and pollutant emissions. The use of alternative sources of energy has been limited to 10% in the last ten years confirming the massive dependance on fossil fuels [3]. Therefore, the search of new ways to generate unexpensive and clean energy is necessary to attenuate the serious consequences of the global and massive use of electricity in the near future.

Jatropha Curcas (JC) is a small tree or large shrub which belongs to the family of Euphorbiaceae and it is considered as second generation biofuel crop [4,5]. Jatropha Curcas usually reaches a height of 2-3 meters but can manage to grow up to 8 meters in especial conditions [6]. Toxic compounds for humans and different animals can be extracted from fruit, seed, oil, bark and leaf of JC, however, this plant can be used as purgative and for several medical purposes such as chemotherapeutic agents [7]. Jatropha Curcas is usually cultivated in zones where extreme temperatures are associated such as Mexico, South America, Australia, Africa and some parts of Asia. The cultivation in terms of hectares of JC has grown more than 85% from 2008 to 2015 because of the swelling interest about the possibilities of this crop and the solid generated after the extraction process has a high upper heating value of 17,2 MJ/kg [8].

Bioethanol can partially substitute traditional fossil fuels because of its high cetane number (108) and suitability in internal combustion engines [9]. Nowadays, three different generations of bioethanol can be found. The first generation is related to the fermentation of glucose presented in starch and sugar. In order to overcome the controversy generated with the first biofuel generation about “food vs fuel”, a second bioethanol generation appeared using residues from lignocellulose, food and agriculture. Lately, third bioethanol generation is related to the production of this biofuel from algae using enzymatic hydrolysis [10]. The use of bioethanol as short-chain alcohol in the transesterification reaction highly improves the production of biodiesel from an environmental point of view. In addition, although the separation between the esters and the glycerol after the ethanolysis is tedious at yields lower than 90%, the low-temperature properties of the ethyl esters are highly improved regarding fatty acid methyl esters [11].

The use of solid catalysts in order to conduct a simultaneous esterification-transesterification of oil and greases with a high content of free fatty acids are currently under thorough study. Moreover, [12] studied the use of sulphated zirconia as catalyst in order to obtain ethyl esters in one single step from crude Jatropha oil. In addition, [13] conducted the same reaction with unrefined oils using Zn nanostar catalyst and metanol as short-chain alcohol at 140ºC, 8 wt% of catalyst content, 15 h and 30:1 methanol:oil ratio with an associated conversión of 99.5%. Finally, [14] studied the use of a biochar-based catalyst in order to perform simultaneous esterification-transesterification reactions of canola oil and oleic acid mixtures with associated conversions near to 50%. Therefore, there is room for further and deeper research in this promising area where the main goal is to make attractive for biofuels production oils and waste with high content of free fatty acids.

This paper deals with the design and economic assessment of an integral valorization Jatropha Curcas plant where the waste related to the extraction of the oil is used in order to generate electricity together with biodiesel derived from the simultaneaous esterification-transesterification process using bioethanol. The catalyst proposed for conducting this simultaneaous reaction is manganese glycerolate which was used by [15] . This catalyst permits to reach a oil conversion of 99.8% at the following reaction conditions: 150ºC reaction temperature, 10 h of reaction time, 20:1 bioethanol:oil ratio and 6 wt% of catalyst content. In addition, the waste produced in the extraction of the oil can be treated and pelletized in order to increase the calorific capacity of the solid which can be burnt to generate steam and subsequent electricity, allowing to improve significantly the economy of the process. The mass and energy flows together with an economical sensitivity analysis were obtained using Aspen Plus and literature showing the feasibility of the proposed plant.

**2. Process description and assumptions**

The flowsheet of the integral valorization Jatropha Curcas can be seen in Figure 1 where two different sectors can be distinguished: biodiesel production sector and generation of electricity sector. In the biodiesel production sector a reactor to perform the simultaneous esterification-transesterification reaction (R-110), a decanter to separate the ethyl esters from the glycerol (D-110) and two flash distillers in order to recycle the surplus of ethanol added in the reactor (F-110) and to purify the biodiesel after the decantation step (F-120) are found. Regarding the generation of electricity sector a dryer (E-110), a pelletizer (P-110), and a biomass boiler (C-110) together with a steam turbine, a pump and a condenser are seen in Figure 1.

According to [16] the percentage of oil extracted from Jatropha Curcas is approximately 17-18%. That means a considerable amount of waste is discarded after the extraction process. As seen in Figure 2, from 6 tons of initial Jatropha Curcas, only 1 ton of biodiesel is produced whereas 2.5 tons of de-oil seed cake and 2 tons of seed shell are generated. Therefore, this solid waste can be treated, pelletized and use as biofuel in a biomass boiler in order to increase the feasibility of the overall process. The de-oil seed cake is mainly formed by hemicellulose, cellulose, lignin and moisture so that it is necessary to remove the humidity, sand, gravel and other solids before compacting the waste and obtain the biofuel.

Crude Jatropha oil has a high content of free fatty acids (12.5%) as published elsewhere [4] and therefore a esterification step needs to be conducted for reducing the acidity of the crude oil. Many authors have carried out a pre-esterification step of the crude Jatropha oil using sulfuric acid as catalyst and afterwards once the acidity is lower than 0.5% the transesterification reaction is perfomed [17]. Although this way to obtain biodiesel from Jatropha oil is not time-consuming and effective (conversion higher than 99%) the amount of washing agent generated for the purification of the product makes the overall process inefficient from economic and environmental points of view. Therefore, the implementation of a new technology that can perform the esterification of the free fatty acids and the transesterification of triglycerides simultaneously using a heterogeneous catalyst could improve noticeably the profitability of the process. This way, the catalyst chosen to perform this study was manganese glycerolate whose preparation and characterization is detailed elsewhere [15] and it permits to conduct the esterification and transesterification of crude Jatropha oil in one single step using bioethanol as short-chain alcohol. The best conditions to perform the reaction using 95 wt% ethanol are: 150ºC reaction temperature, 10 h of reaction time, 20:1 bioethanol:oil ratio and 6 wt% of catalyst content where [15] could reach 99.8% crude Jatropha oil conversion in one step. In conclusion, the use of a heterogeneous catalyst which allows to perform the esterification and transesterification of Jatropha oil in one step, using bioethanol as short-chain alcohol together with the power electricity generation from Jatropha Curcas waste means a significant advance in the way to make the most of this vegetable crop, both economically and environmentally.

1. **Results and discussion**

The plant for the integral valorization of Jatropha Curcas was simulated using Aspen Plus 7.1. As claimed before, two different sectors are differentiated in the flowsheet of the process where on one hand, the oil extracted is converted to biodiesel and glycerol as co-product and on the other hand, the waste generated in the extraction step is treated, pelletized and burnt in order to generate electricity.

* 1. **Jatropha Curcas Plant Simulation**

The initial amount of Jatropha Curcas proposed for this study is the 25000 tons/year and the plant operation procedure is continuous. According to Figure 2, from 25000 tons of JC, 10400 tons of de-oil seed cake, 8333 tons of seed shell and 4200 tons of oil are produced after the extraction process. The de-oil seed cake and seed shell are destined to the creation of pellets but a correction factor of 25% is applied in order to justify the loss of weight of the waste after the pretreatment and pelletization steps. Therefore, 14000 tons of solid biofuel are the main raw material to generate electricity and 4200 tons of crude oil produces biodiesel and glycerol as co-product. Bioethanol with a purity of 95% and manganese glycerolate will also be used in order to carry out the simultaneous esterification-transesterification step. Due to the bioethanol is used in a much higher ratio than predicted by the stoichiometry, a flash distiller is used in order to recycle the surplus at the esterification-transesterification reactor.

* + 1. **Esterification-Transesterification Reactor**

For the esterification-transesterification simultaneous reaction, the crude Jatropha oil oil (stream 10) is added to a continuous stirred tank reactor (CSTR) together with the required amount of bioethanol (stream 9) and manganese glycerolate (stream 8). The simultaneous reaction is conducted in a 13000 l tank reactor (R-110) with an associated stirring blade, at atmospheric pressure (1atm) and a fixed temperature of 150ºC thanks to a heating jacket. After 10 hours of reaction time the mixture is pumped towards a gravitational decanter where the ethyl ester phase is separated from the glycerol phase.

* + 1. **Gravitational Decanter**

The reaction mixture (stream 11) is transferred to the gravitational decanter (D-110) where, after 0.86 h of residence time, the separation of the ethyl esters from the glycerol is produced. The volume of the decanter D-110 is approximately 1100 l. The ethyl esters together with the unreacted oil and the surplus of ethanol are pumped into a flash distiller (F-110) whereas the glycerol phase is also transferred into a flash distiller (F-120) in order to perform the purification steps.

* + 1. **Flash Distillers**

The difference in the boiling points of glycerol, ethanol and ethyl esters permits the use of flash distillers in order to purify the reaction products. Sensitivity analysis using Aspen Plus 7.1 were performed to optimize the Flash Distillers F-110 and F-120. The sensitivity analysis were made establishing a 95 %wt bioethanol requirement from upper of both flash distillers in order to recycle the maximum amount of ethanol at the beginning of the process without a loss of the quality of the reactive for the reaction step. The volumes of the F-110 and F-120 are approximately 1200 l and 200 l, respectively.

* + 1. **Generation of electricity sector**

Regarding the solid waste derived from the extraction of the crude oil is destined to the generation of power electricity using a biomass boiler. Firstly, this part of the process is formed by a pretreatment phase where the impurities and solids contained in the de-oil seed cake and shell (stream 3) are removed, and a dryer for evaporating water presence in the waste. Afterwards, the treated waste (stream 4) is transferred to a pelletizer where the solid biofuel is created and added to the biomass boiler (stream 5). The generation of power electricity is made in the steam turbine and for improving the efficiency of the system a condenser is attached in order to return the water to the biomass boiler. The burnt solid waste should be treated adequately and it is not object of this study.

**3.2 Mass and energy flows**

The mass and energy balance of the integral valorization Jatropha Curcas plant and the sensitivity analysis for the flash distillers were calculated with the software the software Aspen Plus 7.1. As seen in the flowsheet (Fig. 1) there are 19 different streams labeled with a number. The basis of calculation is the initial Jatropha Curcas mass flow and it has a value of 25000 t/ year. The mass and energy balance of the process can be seen in Table 1.

According to the mass balance, the biodiesel mass flow produced in this process is 4700 t/year whereas the glycerol mass flow obtained is 440 t/year, approximately. The stream 19 corresponds to catalyst used that can be recycled thrice [15], and the streams 15 and 16 can be recycled as short-chain alcohol in the simultaneous reaction. The heating value of the Jatropha seed and shell is close to 17.2 MJ/kg, therefore the annual amount of energy generated, taking into account the mass flow of the stream 4, would be higher than 66000 MWh.

* 1. **Economics**

Once the technical aspects of the process have been discussed, the next step is to determine the profitability of a plant with these characteristics. The currency used throughout this economic assessment is the Euro (€) and the value of the equipment and products have been determined by the contact with direct suppliers and data from literature. The biomass boiler and the pelletizer equipment cost supposed for this study were supplied by Sincal® and Pelletsolucion®, respectively. In the Table 1 is charted the most important technical and economic aspects taken into account in this study. The economical factors used for conducting the sensitivity analysis are the Internal Rate of Return (IRR) and the payback time which marked the profitability of the process and the time needed to recover the investment, respectively [18,19]

The influence of the following variables over the economy of the process was studied independently:

1. Price of Jatropha Curcas
2. Price of Bioethanol
3. Price of the catalyst
4. Price of Biodiesel
5. Tax
6. Price of the electricity

The limits and the range established for the mentioned parameters in the economical study can be seen in Table 2.

**3.3.1 Changes in the price of Jatropha Curcas**

The price of the Jatropha Curcas is a determining economic variable because its major influence in the profitability of the process. The price of Jatropha Curcas is marked by the yield of the crop which its usually around 2500 kg per hectare [20]. Therefore, the standard price of the JC supposed for this study is 0.13 €/kg since the price per hectare ascends to 30000 €, approximately [21]. The price of a crop fluctuates heavily because it depends on many factors such as the weather conditions, the cultivation system or the quality of the harvest [18]. That is why the price range fixed for this study is between 0.1 and 0.15 €/kg, as seen in Figure 3, whereas the rest of the considered variables are maintained in its standard values (Table 3). Due to the fact Jatropha Curcas being the main raw material of the process, the payback time is increased as the price of the crop augments and the IRR decreases with increasing the Jatropha Curcas price. As seen in Figure 2, both the payback time and the IRR are very sensitive to the Jatropha Curcas price although the process is still attractive economically at its maximum value because the IRR is close to 9%.

**3.3.2 Changes in the price of Bioethanol**

The simultaneous esterification-transesterification reaction of the crude Jatropha Curcas oil is performed with bioethanol 95 %wt, as claimed in the technical part of this study. For this analysis, a range for the bioethanol price from 0.1 €/kg to 0.5€/ kg was considered. The price of the ethanol can vary importantly depending the purity and the use of this commodity. In this case, the bioethanol needed for conducting the reaction does not need a high purity or special treatments and its price can be close to 0.3 €/l [22]. In addition, more than 80% of the bioethanol introduced in the reactor is recycled because it was introduced in high excess (20:1 ratio) for shifting the reaction towards the formation of products. Therefore, the price of bioethanol of the Jatropha Curcas plant is not a key variable in the profitability of the process as seen in Figure 4. The rest of the considered variables are fixed at its standard level (Table 3).

**3.3.3 Changes in the price of the catalyst**

The influence of the catalyst price on the economy of the process has also been studied through sensitivity analysis. The catalyst proposed for this study is the manganese glycerolate [15] and there is a lack of information about the price of this raw material. However, the information about other metal glycerolates is available for different suppliers such as Huzhou City Linghu Xinwang Chemical Company [23]. The price of Zinc glycerolate in the current market is approximately 3.5€/kg and this price is similar to other glycerolates such as Calcium glycerolate. Therefore, this value gives information about the possible price of the Manganese glycerolate and the range supposed for the catalyst price varies from 3 €/kg to 5€/kg as seen in Table 3. The influence of this variable over the economy of the process is not determinant for the profitability of the process because there is no great changes neither IRR nor payback time with the catalyst price, as seen in Figure 5. As mentioned in the technical part of this study, the catalyst load is 6 %wt and it can be reused thrice without performance loss. Therefore, although the price of the catalyst is initially high this variable does not mark the feasibility of the process from an economic point of view.

**3.3.4 Changes in the price of Biodiesel**

Biodiesel is the main product obtained in the valorization plant, although it is not the main source of benefits because the fundamental variable of the process is the price of the electricity. However, the biodiesel obtained from the crude Jatropha oil is determinant to foresee the profitability of the plant. As seen in Table 3, the range of price supposed for biodiesel is 0.3-0.6 €/l because it is not a product with a fixed price since it depends on several factors such as the price of the petroleum or government funds [19]. Although, the price range proposed is in accordance with the literature [24,25]

As seen in Figure 6, the biodiesel price marks the profitability of the process because the IRR value changes greatly with the value of the biodiesel price. In addition, the payback time varies exponentially at low values of biodiesel price. The process would be completely unaffordable economically if the biodiesel is sold at values lower than 0.36/l. Therefore, the price of the biodiesel should be known in advance with appropriate accuracy in order to assure the economical success of the plant.

**3.3.5 Changes in tax**

All types of chemical processes and products have to deal with different tax percentages and this fact can decide the final profitability of the plant. Therefore, in this case the range for the tax percent supposed in the study varies from 10% to 40% which practically comprehend all the possibilities for the Western Countries [18]. In Figure 7, the effect of the tax percentage over the IRR and Payback time can be seen. Logically, when the tax percent is higher the profits decrease considerable and vice versa. However, the tax percent increase does not mark the profitability of the process because the difference between the lowest and highest value of this variable does not reach 18% in terms of IRR.

**3.3.1 Changes in the price of the electricity**

Finally, the influence of price of the electricity over the economy of the Jatropha Curcas integral valorization plant has been studied. As claimed in the technical part, the seed shell and the de-oiled cake can be pelletized and burnt in a biomass boiler in order to obtain valuable electricity which can be sold in the market. The electricity price range supposed for this study varies from 30€/MWh to 50€/MWh maintaining the rest of the variables in their standard values (Table 3) which covers the majority of possible scenarios. As seen in Figure 7, the electricity price is the most influential variable for the economy of the process because of the amount of waste generated for the extraction of the crude oil (4.5 tons per 6 tons of Jatropha Curcas). Both the IRR and the payback time drastically changes with the electricity price although in the case of the Payback time the tendency is exponential and for the IRR is linear as seen in Figure 8. It can be concluded that the electricity price should be higher than 35€/MWh in order to assure the profitability of the plant.

**4. Conclusions**

This paper deals with the possible feasibility and profitability of integral valorization of Jatropha Curcas plant due to the great amount of waste produced in the crude oil extraction of this seed. Therefore, there are two different sectors in this process: biodiesel production sector and generation of electricity sector. The biodiesel is produced thanks to a simultaneous esterification-transesterification reaction where bioethanol 95wt% and manganese glycerolate are used as short-chain alcohol and catalyst, respectively. The use of this heterogeneous catalyst can avoid the two-step reaction process and tedious purification procedures such as washing and centrifugation. The seed shell and de-oiled cake needs to be pretreated and pelletized before passing through a biomass boiler for obtaining electricity and increasing the profitability of the plant. Therefore, a second generation biofuel which can be used in diesel engines together with a substantial amount of electricity can be obtained for this plant reducing the effects of global warming and greenhouse gases emissions.

The economical study concluded that the process in completely feasible and profitable at certain conditions marked throughout the manuscript. Finally, the variables which have the highest impact over the economy of the process are the biodiesel price and the electricity price because they are the main products of the plant. Nevertheless, the bioethanol price and the catalyst price are the variables with the lowest impact because they can be recycled or reused in the process.

**Disclaimer**

The authors, the NMBU and the Complutense University do not accept responsibility for any decision taken based on these model results. The model used on this work is for research purpose only. For specific applications please contact the authors, as well as for recommendations regarding the limitations and scope of the model.

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