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Study of the Eco-efficiency of Biodiesel Production from the Fruit of the Jatropha Curcas Plant

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In the present study, the Life Cycle Analysis methodology is applied to the production of Biodiesel from Jatropha Curcas, with the objective to identify the stages of the life cycle that affect to a larger extent the environment. This was done by defining the function of the system, the limits of the system, the allocation procedure, the method of environmental impact assessment with its respective categories of impact, and finally, the data quality requirements. During the elaboration of the inventory, each of the basic activities for the Jatropha Curcas cultivation was taken into account. From the conditioning of the ground, followed by the pre-nursery-nursery, field management, and transportation of agricultural inputs. Also, the stages of harvest from the fruit of Jatropha Curcas were included for obtaining the oil and its subsequent transesterification. All this information was acquired in the field, in technical reports, articles and elaboration of simulation for the industrial stages. For the environmental impact assessment of the life cycle, the EPD (Environmental Product Declaration) methodology was used. This methodology is commonly used for the creation of the environmental product declarations. In the economic evaluation of the process, the classic project evaluation methodology was used. This starts with the calculation of fixed capital and working capital investment, salvage values, costs and revenue and after-tax gain. The cash flow net diagram is then constructed with which the decision-making indicators are obtained: NPV (net present value, typically in the year of production start-up), IRR (internal return rate), PT (payback time), and different sensitivity indexes or equilibrium values. With regard to investments and salvage value, it is about values at a certain point in time. Finally, the eco-efficiency of Jatropha Curcas biodiesel was evaluated by relating environmental performance and process profitability. It was found that the production of biodiesel from Jatropha Curcas is not a process with high potential environmental impacts, compared to other commodities. From the economic point of view, it is not viable given the high cost of the seed and the market price of oil.

1. Introduction

The progress of human society has been based on natural systems, which have been a source of resources and waste sinks, but as people were growing and industrializing, the exploitation of ecosystems became intensive, generating important environmental problems. These problems have been reflected in the decrease of the ozone layer, species extinction, the decrease in water sources and the Earth's temperature rise. The highest percentages of participation in this problem, correspond to the use of fossil fuels in industrial activities and transportation (PNUMA, 2012). The general concern about the non-renewable nature of fossil fuels and the air pollution that their use entails has become the force that is driving so that the world to research in alternative sources of fuel, especially of agricultural origin. In Colombia, the consumption of the petroleum-derived fuels is the most used energy source, distributed its use in the transportation sector (90.8%), residential use (8.7%) and industrial use (0.5%). According to this information, it can be thought that the immediate need in terms of renewable energy production should be directed to mobile sources, which are the most polluting in relation to the production of greenhouse gases such as CO2 (Amaya & Becerra, 2009). Obtaining biofuels has been linked to the search for raw materials that optimize the energy efficiency of production processes. In the world, the biodiesel production experienced a growth of 525% between 2000 and

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2006. Studies carried out by the Colombian unit of planning mining energy (UPME) found that Colombia also follows this global trend as fuel consumption shows a strong "Dieselization". Because the highest conversion performance is achieved with palm oil. Colombia started producing biodiesel industrially from this raw material in 2008. It is clear, then, the importance of working with joint efforts to find new tools that allow the evaluation and the proposal of solutions in order to mitigate their environmental impact. One of the tools currently available is the Life Cycle Assessment (LCA) whose objective is to quantify the incoming flows and environmental emissions associated with the life of a product from the extraction of the raw materials to the final disposal of the waste generated throughout the life of the product, methodology known as "from cradle to grave" (ISO 14040, 2016). Therefore, the application of the LCA using the "from cradle to grave" methodology allows identifying the relevant environmental impacts that are caused by the life cycle of a product or service. In addition, LCA it's used as reference point in decision-making and in the comparison of different alternatives available for production. This article covers the study of LCA of biofuel from Jatropha Curcas oil by using "from cradle to grave" approach, which evaluates the eco-efficiency and measures the environmental impacts generated in the production of this biofuel. To evaluate the potential environmental impacts and to obtain the quantitative environmental indicators, ISO 14040 and 14044 standards were used, which include the LCA tool. The LCA was the selected tool since it quantifies the environmental impacts of each stage of production, distribution, and use of the product, from their raw materials production to its disposal as waste.

2. Materials and Methods

The methodology of this study was based on the international standards ISO 14040-14044. According to the standards, the study began by defining the function and limits of the system, the allocation procedure to be used, the method of environmental impact assessment, the impact categories evaluated and finally, the requirements relating to data. Goal definition is one of the most important phases of the LCA methodology, because the choices made at this stage influence the entire study (De Marco et al., 2016). In the second instance, the life cycle inventory was carried out taking into account the stages of cultivation, benefit, oil extraction and transesterification. In the cultivation of Jatropha Curcas the following operations were taken into account: soil preparation, pre-nursery, nursery, sowing, fertilization, harvesting and transport of agricultural inputs. All the information required for the crop inventory was obtained through review of technical documents, visits to crops and by consulting with producers. For the stage of oil production, a pressing equipment was used. This equipment was observed in several of the visited fields. The process of converting vegetable oil into biodiesel fuel was based on the transesterification reaction of Jatropha Curcas with methanol by using sodium hydroxide as catalyst. Since in Colombia there are not Jatropha Curcas biodiesel production plants on an industrial scale, the inventory analysis for this stage was carried out by constructing the mass and energy balances of the process in a process simulator: UniSim®. This software helps engineers to create dynamic models for plant design, the monitoring of performance, the problem-solving, business planning and asset management in the steady state. The third step of the LCA methodology consists of the environmental impact assessment. SimaPro® software was used for its realization. The inventory data were introduced into the computational tool and the environmental impacts associated with the product were calculated throughout its life cycle. SimaPro® software has the option to select the calculation methods for the environmental impacts assessment. The Environmental Product Declaration (EPD) method was selected in the present analysis because it is commonly used for biofuel LCAs (Kim and Dale, 2005). Since the eco-efficiency of a product or process is quantified by calculating the relationship between the environmental performance and financial performance of the company (see equation 1) in parallel with the environmental impact assessment, the economic evaluation of the stages of the product lifecycle was carried out.

$$Eco-efficiency = \frac{Value\ of\ product\ or\ service}{Environmental\ influence} \tag{1}$$

The economic evaluation was performed using the classic methodology of project evaluation, which includes fixed capital and working capital investment calculations, salvage values, costs, and incomes. It also assessed the after-tax gain taking into account the Colombian context, in order to have the net cash flow diagram, which gives the indicators for decision making: NPV (net present value, typically in the year of production start-up), IRR (internal return rate), PT (payback time), and different sensitivity indexes or equilibrium values. The costs and incomes were calculated year by year and, in order to add them, each value were converted in pesos of the initial year of the project (time base). The fixed investment and working investment was evaluated using the purchase value of the fundamental equipment in the processes.

3. Results and discussion

In the first instance, the objective of the LCA was defined: quantify the environmental impacts generated in the production of biodiesel from Jatropha Curcas by considering the stages of cultivation, benefit, oil extraction and transesterification. Once the objective of study has been given, it was defined as the functional unit 1 kg of Jatropha Curcas biodiesel. The allocation procedure applied in all stages of the process was the mass, this is considered to be more objective in systems multiproduct (Ahlgren et al., 2014). For the environmental impact assessment, the EPD method was selected since it includes the impact categories that are normally evaluated in LCA studies of biofuels (Martinez et al., 2010). The data taken for the evaluation comes from different sources. For the stages of cultivation, benefit, oil extraction we took primary data, while for the transesterification stage it was necessary to use the secondary data from calculations made using bibliographical review and computational tools. Once scope and objectives of the evaluation were fixed, it was possible to perform the life cycle inventory (LCI). The LCI began in the cultivation since it is one of the activities of major importance in the studies of the environmental impact of biofuels. A cultivation of 15 hectares was taken as a basis. The selected seeds have the characteristic that once planted they give as result, crops that will last 40 years. These seeds can be planted with a density of 2500 seedlings per hectare (Sandino et al., 2012). Fuel costs for machinery and the transport of agricultural inputs such as seeds, fertilizers, and fungicides were considered. In the post-harvest stage, a proper management must be carried out since the fruit begins to decompose quickly. For this reason, it is recommended to extract the oil in the same facilities of the crop and at the same time composted the pulps and residual husks of the operation. Two methods exist for crude Jatropha oil extraction: solvent and mechanical extraction. Solvent extraction is common in the processing industry and can provide higher oil yields; however, it is only profitable at a large-scale production, for this reason, mechanical extraction is more common (Beaver et al., 2016). Once the oil is obtained, its transformation into biodiesel is achieved through a transesterification process. As shown in Figure 1, the process starts with the mixture of sulfuric acid (H2SO4) and methanol (MeOH), which is pumped and preheated in the mixer (MIX-100). The mix obtained is pumped and preheated before entering into the reactor (CRV-100). Also Jatropha Curcas oil, previously heated, is pumped into the reactor CRV-100. The reactor is operated at 60 °C and converts the free fatty acids to methyl esters.

The resulting stream subsequently passes through separation and purification steps (V-100 and T-100) with the aim of recovering and recirculating the methanol that did not react in the process. For its part, the stream rich in methyl esters and acids fatty (200, in Figure 1) is led to a second reactor (CRV-101) where it is reacted with a solution of methanol and hydroxide of sodium previously heated. In this second reactor is performed the transesterification of the oil whose result is biodiesel. The reactor output stream is then carried to the tower (T-100) where it is washed and separated: glycerol and biodiesel. The biodiesel rich stream has then carried another separator in which it is possible to extract impurities and obtain biodiesel under commercial conditions. Instead, the glycerol is passed through a heater and then through a tower (T-103) where the alcohol and glycerine are separated.

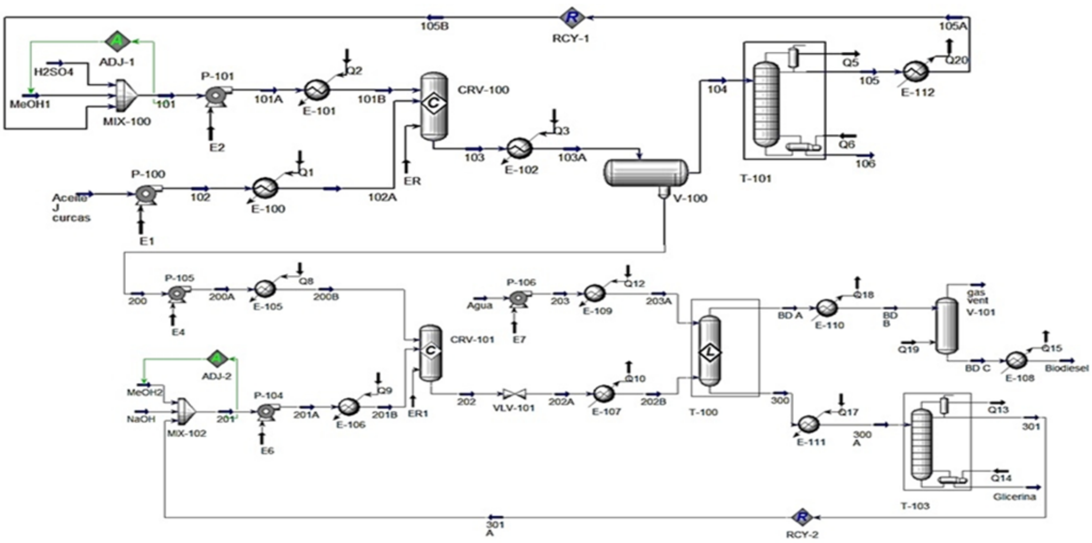

Figure 1: Simulation stage of obtaining biodiesel

The mass and energy balances of the cultivation and transesterification stages were introduced in SimaPro® software with the objective of evaluating the environmental impact of Jatropha biodiesel. In the stage of transesterification it was necessary to use an allocation method due the production of glycerol as co-product. The mass allocation method was selected for this case in order to distribute the environmental impacts in an objective way. The method was applied as standard ISO 14044:2006 suggests it. Figure 2 summarizes the results of the impact assessment for each of the impact categories evaluated.

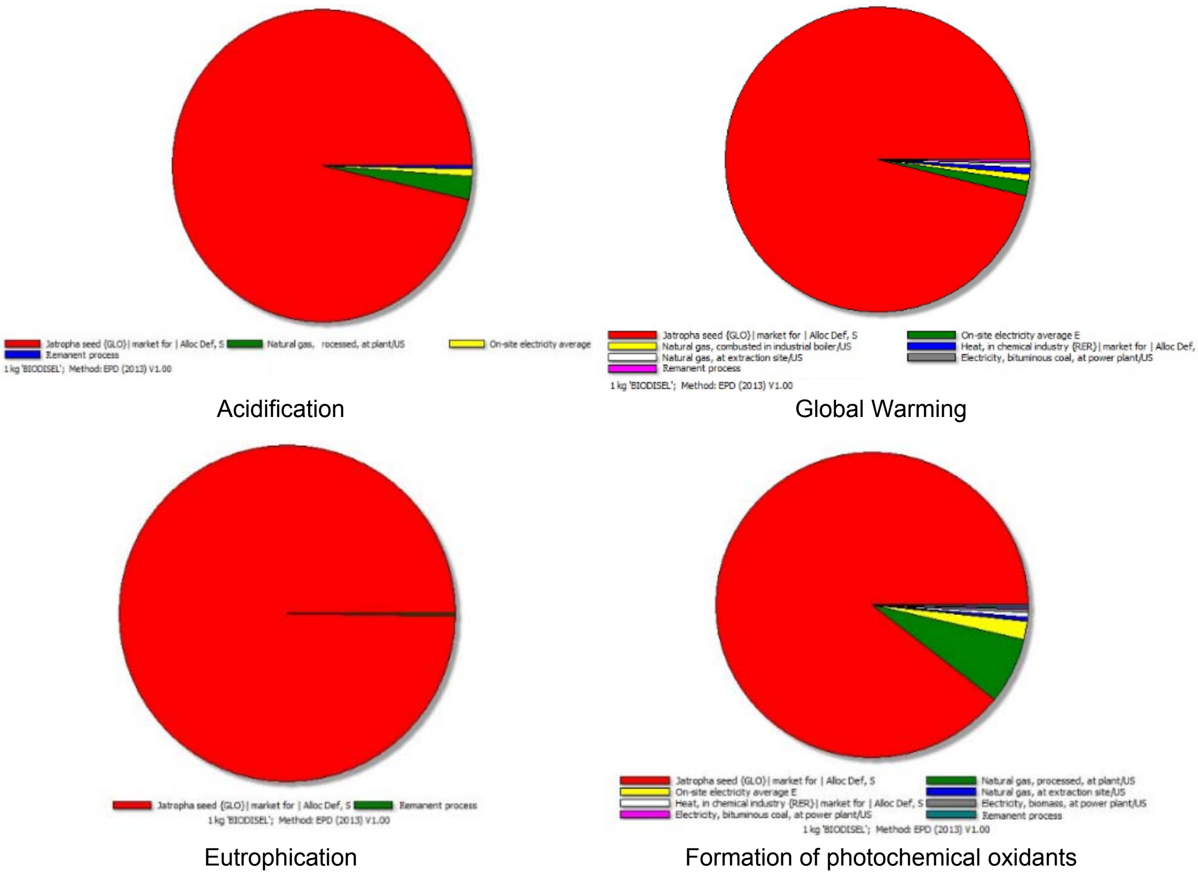

Figure 2: Life cycle impact assessment results of 1 kg of biodiesel of Jatropha Curcas

As can be seen from Figure 2, the production of Jatropha Curcas seeds is the life cycle stage that more contributes to generate negative environmental impacts. This result is similar to the obtained in the case of biodiesel from soybean, were the land use impacts (due to occupation and transformation) account for 76.02% of potential environmental impacts in the soybean agriculture stage (Morais et. al., 2010). The acidification, generated mainly by emissions of ammonia, sulphur dioxide, and nitrogen oxides, is affected in the cultivation stage by the consumption of fossil fuels and the use of volatile nitrogen fertilizers. In the climate change indicator, the highest percentages of participation are due to the change of land use, the use of fossil fuels for crop operations and the energy expenditure of the industrial stages. Figure 3 shows the main emissions into the air that impact in this category and it is observed that carbon dioxide emitted during the land transformation is the main contributor. The other emission that stands out is the di-nitrogen monoxide that comes from the use of diesel in the cultivation stage.

The use of crop residues and animal faeces as fertilizers in the crop generates the eutrophication impact. These emissions could be avoided if the selection of the fertilization scheme depends on the environmental priority.

In the category of formation of photochemical oxidants, it was again found that the greatest contributions are due to the use of fossil fuels for crop operations and the energy consumption of the industrial stages. The most relevant emissions in this impact category are sulphur dioxide and carbon monoxide.

For the economic evaluation of the life cycle, calculations of economic indicators for two main stages were made. It considering that extraction of the oil is carried out in situ.

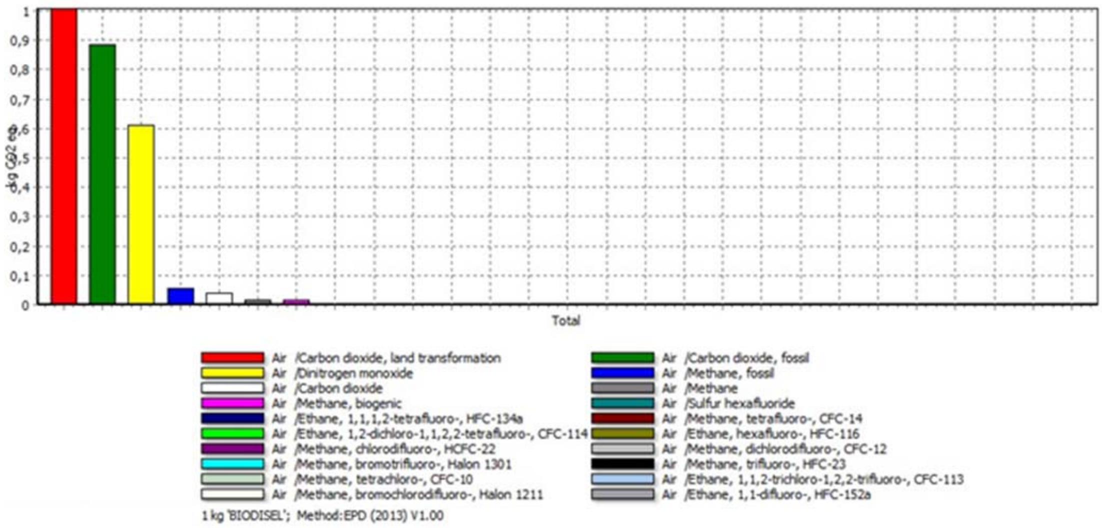

Figure 3: Air emissions that affect the category global warming.

The first stage considered includes cultivation, harvest, and oil extraction. The second stage is focused on the process of conversion of Jatropha Curcas oil into biodiesel. The costs in both stages were calculated by knowing the number of raw materials, the price of raw materials, amount of industrial services and the price of services, manpower quantity, administrative costs, maintenance costs and prices for proper activities of each stage. Among the inputs are consulted: seeds, fertilizers, among others. For the cost of labour, the Colombian wage tables along with the corresponding performance factor were taken into account. The revenues in the first considered stage come mainly from the sale of Jatropha Curcas oil, while for the second stage the revenues come from the sale of biodiesel and glycerol. For the gross margin was taken into account the income, unit costs, and labour costs. To evaluate the net present it was considered a minimum attractive rate of 15% as a reference. The time of the first stage (cultivation, harvest and oil extraction) was set at 40 years, while for the biodiesel plant is fixed 20 years. Under these circumstances, it was found that the recovery of the investment in the first stage is given after 3 years and it was found that the crop has an internal rate of return of 46.43%. To estimate the evaluation of the industrial transesterification plant, the flows obtained in the simulator of a plant with a production capacity of 96,163,200 kg/y were considered. In this second stage, it was found that the costs in all the years considered are greater than the incoming for the biodiesel and glycerol sells. After performing some sensitivity analysis it was found that the costs were particularly high because of the price of Jatropha Curcas oil. Since eco-efficiency is a relationship between environmental performance and financial performance of the life cycle, and that the Jatropha Curcas biodiesel production is not economically feasible in Colombia, it is concluded that Jatropha Curcas biodiesel is not eco-efficient for the Colombian context

4. Conclusions

The crop is the most significant life cycle stage in Jatropha Curcas biodiesel life cycle, representing almost the total of the potential environmental impacts. This was evidenced in the four categories of impact evaluated: acidification, global warming, eutrophication, and formation of photochemical oxidants.

The production of Jatropha Curcas oil in Colombia is a profitable business from the economic point of view, due to the market oil price and the relatively low cost of the land in the country.

The Jatropha Curcas biodiesel presents an environmental performance comparable to other biofuels such as African palm and castor bean, however, is not eco-efficient for the Colombian context since the transesterification on an industrial scale of Jatropha Curcas oil is not a viable process from the economic point of view. .

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