CHEMICAL ENGINEERING TRANSACTIONS
VOL. 50, 2016
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Katharina Kohse-Höinghaus, Eliseo Ranzi

ISBN 978-88-95608-41-9; ISSN 2283-9216
DOI: 10.3303/CET1650073

Life Cycle Analysis of Jatropha Curcas as a Sustainable Biodiesel Feedstock in Argentina

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Despite constant changes to the industry in recent years, Argentina remains one of the most important producers of biodiesel in the world. Approximately 90% of the biodiesel produced in Argentina is from soybean, a fact which has raised concern over the fuel's sustainability. For this reason, alternative crops such as Jatropha curcas are being explored. The aim of this study is to assess the environmental impact of Jatropha-based biodiesel for the specific case of Argentina through life cycle assessment (LCA). The processes considered in this study include Jatropha seed cultivation, seed transportation, oil extraction, and transesterification. Two cultivation scenarios are examined in order to explore trade-offs between land use type and agricultural inputs. This study also incorporates land and water use, which are typically omitted from LCA due to complexity and lack of available information. Inventory data for the system were collected and analyzed using the ReCiPe impact assessment method. The results show a 21% reduction of kg CO2 equivalent for the overall Jatropha biodiesel production process when using fertile land with low-input agriculture instead of marginal land use with fertilizer and irrigation.

1. Introduction

Growing concerns related to energy security and climate change initially sparked the interest and investment in biofuels as an environmentally friendly alternative to traditional fossil fuels. In recent years, however, biofuels have come under closer scrutiny based on possible competition of feedstocks with food sources, impacts of land use change, and relatively low reduction of—or even in some cases, increases in—greenhouse gas (GHG) emissions. For this reason, in an effort to evaluate the environmental, economic, and social impacts of biofuels, global sustainability criteria are being developed (FAO, 2013). These criteria will become increasingly important to the global biodiesel market in coming years and of particular interest to countries with export-based biodiesel markets, such as Argentina.

Currently, 90% of Argentina's biodiesel is currently produced from soybean. This fact has raised concerns with respect to the fuel's sustainability, as agricultural practices such as mono-cropping and the use of genetically modified crops are widespread throughout Argentina (Milazzo et al., 2013). Land-use change for soybean cultivation also has a major environmental impact, as a study of soybean biodiesel production in Portugal showed that land-use impacts account for 76% of the potential environment impacts of the agricultural stage (Morais et al., 2010). In the specific case of Argentina, it has been projected that the country will not be able to meet future production and exportation targets with soybean alone without significant deforestation (Herrera et al., 2013).

Based on this, Argentina has started to research alternative biodiesel feedstocks, such as Jatropha curcas. Jatropha boasts a long list of advantages including a lifespan of 30 to 50 years, high seed oil content of up to 42% compared with 14% for soybean, and potential annual dry seed yields between 1.5-7.8 tons per hectare (FAO, 2010). Jatropha can also grow in marginal, nutrient-poor soils thus reducing land competition between energy and food crops (Achten et al., 2008). Over time, however, many global field trials of Jatropha have failed, as the plant has very unpredictable yields and falls victim to pests, diseases, and frost (Carrizo, 2011). Perhaps the greatest disappointment is that while Jatropha can grow in marginal lands, the plant will not achieve optimal yields under these unfavourable conditions. Prueksakorn and Gheewala (2008) suggest that

Please cite this article as: Beaver A., González Castano F.A., Diaz M.S., 2016, Life cycle analysis and multi-objective optimization of jatropha curcas as a sustainable biodiesel feedstock in argentina, Chemical Engineering Transactions, 50, 433-438 DOI: 10.3303/CET1650073

Jatropha cultivated on marginal land in the case of Thailand required double the amount of energy to yield the same amount of seeds as when cultivated on fertile soil. This reveals that the sustainability of Jatropha depends heavily on the land-use decision and that the sustainability benefit of the crop may be diminished if it must be planted in fertile, nutrient-rich soil.

The purpose of this study is to complete a crop- and country-specific LCA to provide insight into Jatropha's sustainability as a biodiesel feedstock in Argentina. Two different cultivation scenarios are also considered in order to evaluate environmental trade-offs between using fertile land with low-input agriculture versus marginal lands with high fertilizer use and irrigation. The system boundary for this study includes the processes of Jatropha seed cultivation, seed transportation, oil extraction, and transesterification. The Midpoint ReCiPe impact assessment method was chosen for this study (Goedkoop et al., 2008).

2. Methodology

The study was conducted according to the framework defined by International Organization for Standardization (ISO) 14040 standard. The requirements for this standard include (i) goal and scope definition, (ii) life cycle inventory analysis, (iii) life cycle impact assessment, and (iv) data interpretation.21

2.1 Goals and scope definition

The aim of this study is to assess the environmental impact of Jatropha-based biodiesel production in the specific case of Argentina. The studied system includes Jatropha cultivation, seed transportation, crude oil extraction, and transesterification. The study also evaluates two distinct cultivation scenarios in order to explore environmental trade-offs related to land use change and agricultural inputs.

2.2 Functional unit and system boundary

The system boundary for this study is indicated in Figure 1 below. The processes analyzed include (i) Jatropha cultivation, (ii) seed transportation, (iii) Jatropha oil extraction, (iv) biodiesel production through alkali-catalyzed transesterification reaction. The functional unit used is 1 ton of Jatropha biodiesel produced.

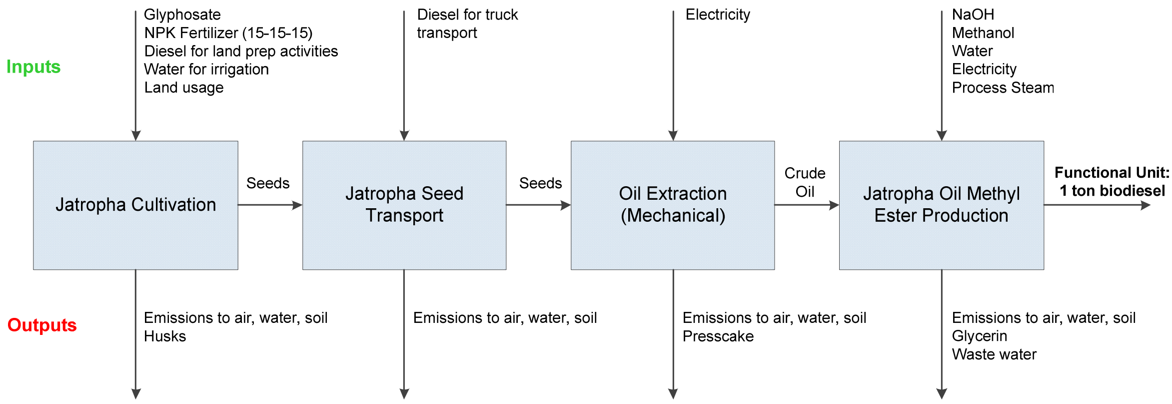

Figure 1. System boundary for Jatropha-based biodiesel production life cycle assessment

2.3 Data collection and inventory analysis

Data for this study were collected through interviews, seminar proceedings, literature, and crop- and country-specific processes available in Ecoinvent v3.0 database. In the event that data for Argentina or Jatropha were not available, data for another country or crop was used and is indicated as such below.

2.3.1 Jatropha cultivation

This study is unique in that it utilizes yield data specific to Argentina. Two cultivation scenarios were evaluated in order to explore the impacts of land-use type and agricultural practices. The Formosa province scenario (Case 1) was modelled after an existing plantation using field data and information obtained from past employees. Plant density at the plantation is 1250 plants per hectare. Reported yields for the year 2014 were 1400 kg of seeds per hectare. This yield is also aligned with literature values predicted for the region (Trabucco et al., 2010). No irrigation is used, as Formosa has been characterized as having "optimal aptitude" with respect to annual precipitation for Jatropha cultivation based on aptitude maps developed for Argentina (Falasca and Bernabé, 2009). Aside from initial field preparation with an NPK Triple 15 fertilizer, no additional fertilizer is used. The initial fertilizer requirements for the plantation were determined based on the minimum amount needed for nutrient removal of fruit (Achten et al., 2008). Minimal amounts of glyphosate are used as needed to manage insects and diseases.

A second, theoretical scenario for the Santiago del Estero province (Case 2) was used to represent Jatropha cultivation on marginal but Jatropha-suitable lands with irrigation and fertilizer. Santiago del Estero was selected for this scenario based on the aforementioned agro-climatic maps. An assumption of 151 kg/ha for each nutrient was assumed based on recommendations from literature (FACT, 2010). While the biomass and seed cake from Jatropha has been shown to be very nutrient rich and an alternative fertilizer source, this practice is not widely accepted in Argentina yet. In order to represent current cultivation practices, NPK Triple 15 fertilizer was also used for this scenario. Irrigation requirements were determined using CLIMWAT 2.0 and CROPWAT software from the Food and Agricultural Organization of the United Nation (FAO) along with crop-, soil- and region-specific data. The irrigation process used from the Ecoinvent database is for Brazil, as an Argentina-specific process was not available.
Diesel requirements for field preparation were taken from literature and available planting, tilling, and irrigation processes in the Ecoinvent database (Reinhardt et al., 2008). Emissions to air, water, and soil from fertilizer and glyphosate use were calculated according to IPCC Tier 1 guidelines as well as the Ecoinvent manual for direct emissions.

2.3.2 Land use change considerations

Two types of direct land-use change are included in this LCA: land occupation and land transformation. Occupation is defined as the continuous use of land area for a certain human-controlled purpose. Transformation is the irreversible change in the purpose for which land is used by humans (Koellner et al., 2013). Jatropha is modelled as a permanent crop based on the plant's lifespan and the fact that after initial plantation, no further field preparation is required. Formosa was modelled as having extensive (low-input) agricultural practices and Santiago del Estero, intensive (high-input), based on use of fertilizer, pesticides, and irrigation. It is typically uncommon to know the exact prior land-use when carrying out a life cycle assessment; however, in the case of the existing Formosa plantation, information was obtained through interviews and seminar proceedings to provide an accurate view of land-use change. The quantity of land was calculated based on yield and equations from literature for occupation and transformation.

Table 1: Data inventory of agricultural inputs for cultivation of 1 kg Jatropha seeds.

Inputs	Case 1	Case 2
NPK Fertilizer	3.4022×10^{-3}	3.59×10^{-2}
Glyphosate [kg]	1.2138×10^{-4}	1.2138×10^{-4}
Diesel, field preparation [kg]	9.14×10^{-3}	9.14×10^{-3}
Diesel, irrigation [kg]	-	4.46×10^{-5}
Water, irrigation [m^3]	-	4.127×10^{-4}
Occupation [m^2 y]	7.14 (Permanent crop, non-irrigated, extensive)	7.14 (Permanent crop, irrigated, intensive)
Transformation, to [m^2]	0.357 (Permanent crop, non-irrigated, extensive)	0.357 (Permanent crop, irrigated, intensive)
Transformation, from [m^2]	0.357 (Agriculture)	0.357 (Shrubland)

2.3.3 Seed transport

The processes of harvesting and de-husking of Jatropha fruits are typically done manually and have therefore not been included in this study. It is assumed that this work is completed at the plantation and then seeds are transported to the biodiesel production plant to undergo both extraction and production. The transport method is assumed to be truck, which is favored in Argentina due to lack of maintenance to railways. Because 90% of Argentina's biodiesel capacity is installed in the Santa Fe province, average distances between Formosa and Santiago del Estero provinces to Santa Fe province were used (Andersen et al., 2012).

2.3.4 Oil extraction

Two methods exist for crude Jatropha oil extraction: solvent and mechanical extraction. Solvent extraction is common in the soy-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 in Argentina. Oil recovery efficiency for engine-driven screw presses ranges from 75 to 80% and is assumed to be 80% for this study (FAO, 2010). Energy requirements were determined based specifications for a common screw-press model and vendor in Argentina. An available Argentina-specific electricity process was used from the Ecoinvent database. Seed oil content is assumed to be 32% based on an analysis completed for Jatropha seeds cultivated and harvested in Argentina (Huerga et al., 2010b). While the nutrient-rich presscake from the extraction process can be used as fertilizer, this is not yet a common practice in Argentina. Thus, the presscake was considered to be organic waste in this study.

2.3.5 Biodiesel Production

Sodium and potassium hydroxide continue to be the most prominently used catalysts for biodiesel production in Argentina. For this reason, sodium hydroxide was selected for this study. The mean fatty acid content of crude Jatropha oil ranges from 0.18 to 3.40% (Achten et al., 2008). These values are also in accordance with experimental studies carried out in Argentina. A study by Argentina's Instituto Nacional de Tecnología Agropecuaria (INTA) recommends that oil with less than 2% fatty acid can undergo transesterification without neutralization and esterification steps (Huerga et al., 2010a). For this reason, a transesterification reaction with methanol and sodium hydroxide has been selected with a methyl ester yield of 90% (Berchmans et al, 2008).

Table 2: Data inventory for oil extraction and transesterification processes

Inputs	Value	Inputs	Value
Oil extraction efficiency [%]	75	Transesterification efficiency [%]	90
Seed oil content [%]	32	Electricity [kWh t^{-1} crude oil]	31
Screw press capacity [kg seed h^{-1}]	200	Process Steam [MJ t^{-1} crude oil]	619
Screw press power [kW]	11	Sodium hydroxide (NaOH) [kg t^{-1} crude oil]	14
Electricity [kWh t^{-1} seed]	55	Methanol [kg t^{-1} crude oil]	240

2.4 Life cycle impact assessment

SimaPro 8 software was used to perform the life cycle assessment. The impact assessment methodology selected was ReCiPe (Goedkoop et al., 2008). This method was chosen based on its successful implementation in other biodiesel LCA's (Pieragostini et. al, 2014). There are 18 available midpoint categories, which connect the results of the life cycle impact to three broader damage categories of human health, ecosystem quality, and resources. Husks and presscake were considered waste in this LCA to best represent the current situation for Jatropha in Argentina. Mass allocation was used to consider the glycerin by-product.

3. Results and Discussion

In accordance with ISO 14040, characterization of the inventory data was performed. Results are based on the hierarchical perspective of ReCiPe (Goedkoop et al., 2008). Figure 2 shows a comparison of the characterization of the two cultivation scenarios. The comparison reveals that for all impact categories, the Santiago del Estero cultivation scenario on marginal land with high agricultural inputs has a greater environmental impact. A 77% reduction of kg CO_2 equivalent is observed when using fertile, low-input agriculture versus marginal lands with irrigation and fertilizer inputs.

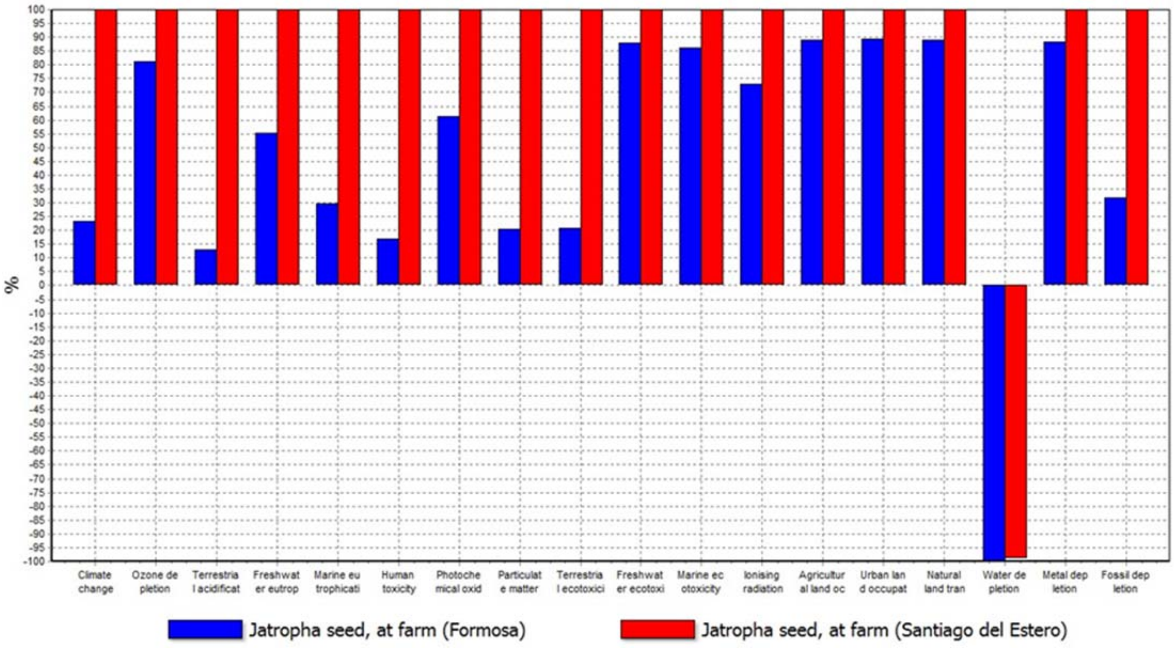

Figure 2: Comparison of midpoint impact categories for two Jatropha cultivation scenarios

Of the 18 impact categories from ReCiPe, the Formosa scenario demonstrates the most beneficial effects in terrestrial acidification, human toxicity, and particulate matter formation, with percent reduction compared to the Santiago del Estero scenario of 87%, 83%, and 80%, respectively. This is most likely a result of the increased use of fertilizer for the Santiago del Estero case.

Both cultivation scenarios show a positive environmental impact with respect to water depletion. This may be due to the fact that no natural water sources are used in this model, and all water used is included in the irrigation process (or not included at all in the case of Formosa). Also, the irrigation requirement calculated for Santiago del Estero is relatively small when compared to that used in the default cultivation processes in the Ecoinvent database for Jatropha, globally (0.0853 m^3) and soybean in Argentina (13.1 m^3).

With respect to land-use impact categories, there appears to be no environmental benefit to using marginal shrubland versus agricultural land. This may be due to the fact that because the land was previously agricultural land, the impact of land-use change is minimal, and in fact based on the numbers, less than the impact to shrubland. In other words, the conversion of shrubland, although it is considered to be marginal land, may have a greater negative impact on biodiversity than land previously used for agriculture.

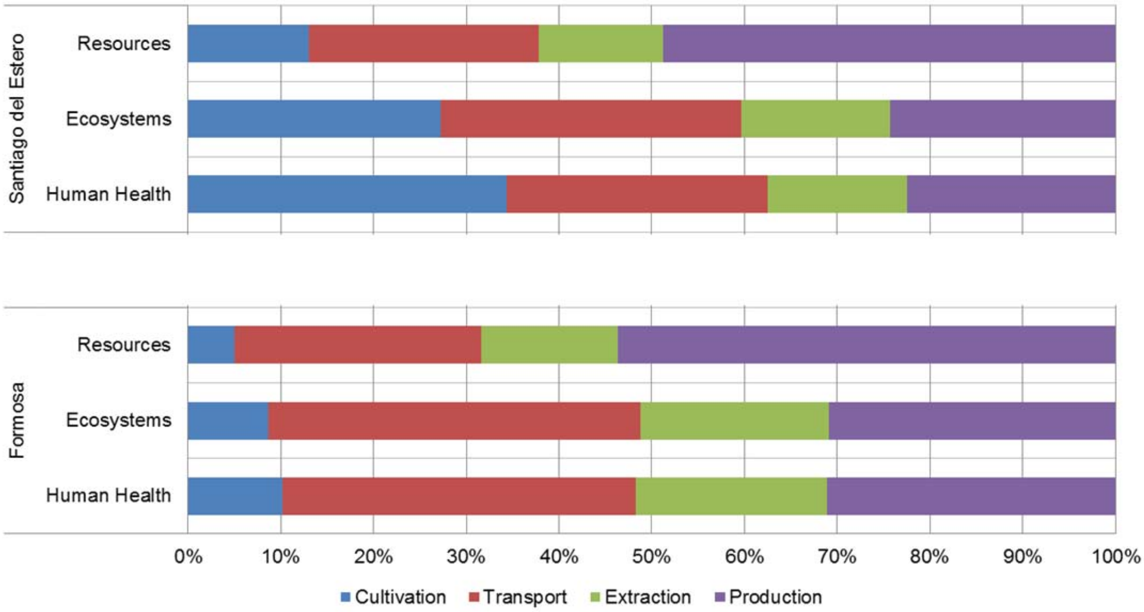

Figure 3: Comparison of Jatropha biodiesel production process for two cultivation scenarios

For the overall Jatropha biodiesel production process, a 21% reduction in kg CO_2 is seen for the Formosa case when compared to Santiago del Estero case. Figure 3 provides a comparison of the three damage categories for the complete production process, considering the two different cultivation scenarios. As expected, the two processes have comparable impacts with respect to extraction and production, as the seeds from both cultivation scenarios utilize the same processes. The greatest difference, as noted above, can be appreciated in the cultivation process. For the overall production process, a percent reduction of 28%, 21%, and 9% is seen for the Formosa case versus Santiago del Estero for the damage categories of Human Health, Ecosystems, and Resources, respectively. Appreciated

4. Conclusions

The environmental impact of Jatropha biodiesel production for the case of Argentina has been evaluated using LCA methodology. Two distinct cultivation scenarios were considered in order to assess trade-offs between land-use type and agricultural inputs. A reduction of 77% and 21% of kg CO_2 equivalent is seen in the case of Formosa versus Santiago del Estero for the cultivation stage and overall Jatropha biodiesel production, respectively. This suggests that the use of marginal land may not provide an environmental benefit, as increased fertilizer and irrigation are needed to achieve desired yields. Future work includes evaluation of the economic and social impacts of Jatropha biodiesel production and a comparison with soybean based biodiesel in Argentina to provide further insight into the crop’s sustainability.

Acknowledgments

The author acknowledges the financial support received from the United States Fulbright Student Program and the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). The author would also like to thank the technical experts from INTA and the Formosa plantation for offering their support.

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