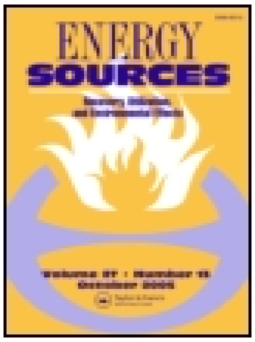

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Energy Sources, Part A: Recovery, Utilization, and Environmental Effects

ISSN: 1556-7036 (Print) 1556-7230 (Online) Journal homepage: http://www.tandfonline.com/loi/ueso20

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To cite this article: Pedro A. Rodríguez Ramos, Lourdes Zumalacarregui De Cárdenas, Osney Perez Ones, Ramón Piloto-Rodríguez & Eliezer Ahmed Melo-Espinosa (2018): Life cycle assessment of biodiesel from *Jatropha Curcas L* oil. A case study of Cuba, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, DOI: 10.1080/15567036.2018.1487479

To link to this article: https://doi.org/10.1080/15567036.2018.1487479

Published online: 27 Jun 2018.

ENERGY SOURCES, PART A: RECOVERY, UTILIZATION, AND ENVIRONMENTAL EFFECTS
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Life cycle assessment of biodiesel from *Jatropha Curcas L* oil. A case study of Cuba

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ABSTRACT

The aim of this research is to identify and quantify the categories which have the largest environmental impact in the biodiesel production process from *Jatropha curcas* L oil. The *Jatropha curcas* L is selected due to its availability in Cuba, so 400 L/d was defined as a functional unit. The valorization analysis was conducted taking into account the conventional *Jatropha curcas* L oil production. The analysis is conducted based on several factors such as the use of synthetic fertilizers, pesticides, and agriculture wastes. The activities of agriculture and industrial stages are shown. The Life Cycle Assessment is addressed according to the ISO 14040 series, by using the Ecoinvent database 2003 and the Eco-indicator 99 methodology. Based on the obtained results, the environmental performance of the production of biodiesel from *Jatropha curcas* L oil has a good environmental behavior. The agriculture stage shows the greatest impact due to land use and fossil fuel depletion. In addition, electricity has the highest impact due to respiratory effects from the emission of tiny material particles into the atmosphere.

KEYWORDS
Biodisel; environmental impact; *Jatropha curcas* L; life cycle assessesment; vegetable oil

Introduction

In many countries, energy is produced using fossil fuels. The finite fossil fuel reserves, greenhouse gas emissions and related global warming, volatility fossil fuel prices and their influence on energy scenarios are currently worldwide problems (Melo-Espinosa et al. 2018). Some strategies to reduce the dependence on fossil fuels are taken into consideration. The world has to change the energy production based on fossil sources to one based on renewable sources. The growing concern about the environment and the influence of the use of fossil fuels on global warming have intensified the search for alternative fuel sources, especially bioenergy.

Fuels from biomass have had a tremendous growth in the world due to the need of finding a better form to produce energy in a sustainable way. Biofuels production from vegetable oils is widely considered one of the most sustainable alternatives to diesel fuel (Melo-Espinosa et al. 2017). *Jatropha curcas* L (*JCL*) biomass could be part of the solution, at least at a local scale. *Jatropha curcas* L is a promising and unconventional biomass. In this study, medium-scale production of biodiesel is investigated. Cuba is the geographical location selected for this study. It has favorable conditions: privileged land and climate conditions to diversify land for obtaining food, electricity, and biofuels from biomass, especially the *JCL*.

JCL is a non-toxic and drought resistant tree that grows well in low fertility soils. It is relatively easy to harvest and it has a long life yield. It is a tall bush or small tree (up to 5 *m* high) that belongs to the euphorbia family. There are approximately 170 known species of genus Jatropha. The tree is

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planted as a hedge (living fence) by farmers around homesteads, gardens, and fields, because it is not browsed by animals. *JC*L, or physic nut, has thick glabrous branchlets. The tree has a straight trunk and gray or reddish bark, masked by large white patches. It has green leaves with a length and width of 6 to 15 cm, with 5 to 7 shallow lobes. The leaves are arranged alternately. Some others interesting features of *JC*L settled in Cuba, can be consulted in (Machado and Suárez 2009; Sotolongo 2007).

The first energy crops were developed (there are over 100 ha of land planted of *JC*L in highly degraded soil) in Cuba, at Guantanamo and Granma provinces. These experiences were boosted by the Ministry of Science, Innovation, Technology and Environment (CITMA), the Sugar Industry (AZCUBA) and supported by the Ministry of Industry (MINDUS) (Sotolongo 2007).

Since 2009, the BIOMAS-CUBA project coordinated by Indio Hatuey Experimental Station began planting this tree associated with food crops and the first biodiesel plant in Guantanamo was installed in 2012. This project has established over 400 *ha* at Granma, Holguin, Guantánamo, Las Tunas, Ciego, Sancti Spiritus, and Matanzas provinces and will reach more than 1500 *ha* for 2024.

In Cuba, *JC*L is a culture with high production capacity. If the leaves and tops, which are not used for oil production, are included, the biomass volume would rise. (Machado and Suárez 2009; Sotolongo 2007). It has been demonstrated that the use of *JC*L to obtain renewable energy is very attractive, since biomass, *JC*L by-products, and their use for energy are in principle climate-neutral since the plant closes the carbon cycle. Each tree captures about 6 *kg* of CO_2 and releases about 9 *kg* of O_2. Each ton of consumed biodiesel can decrease in 200 *t* CO_2, by substituting petroleum; besides it contributes to reducing SO_2 emissions by obtaining a free sulfur content biofuel. Biodiesel is less carcinogenic than fossil fuels (Machado and Suárez 2009; Sotolongo 2007).

Biodiesel fuels are classified as fatty acid methyl esters (FAME), which are derived from the alkali-catalyzed transesterification of oils or fats with methanol. Biodiesel according to governmental regulations and standards is defined as FAME which is the result of the reaction of fatty acids with methanol (Piloto-Rodríguez et al. 2010).

The benefits below are recognized for using the *JC*L oil in biofuel production (Kumar, Chowdhury, and Al Basir 2016; Rodriguez et al. 2009; Sotolongo 2007):

- It can help to reduce air pollution and related public health risks.
- It reduces pollution greenhouse gases (in Latin America and the Caribbean projects may qualify as Clean Development Mechanism to reduce the generation of CO_2 from fossil fuels).
- It contributes to diversifying the national energy matrix through renewable sources.
- It might reduce the dependence on external fossil fuels.
- It is a promising solution to the problems created by climate change and energy insecurity.
- The biodiesel from Jatropha has the potential of providing a promising and commercially alternative to diesel oil since it has physicochemical and performance characteristics comparable to diesel fuel.

The main goal of this investigation is to identify, quantify and compare the environmental impact categories of biodiesel production from *JC*L oil, to evaluate the potential advantages and the magnitude of life cycle balances.

Materials and methods

Life Cycle Assessment (LCA) is the compilation and evaluation of inputs, outputs and potential environmental impacts of a product system throughout its life cycle. This methodology quantifies environmental impacts of the whole process by considering the source of all inputs and the destination of all products and wastes, in order to assess the sustainability charge of a process (ISO 14040 2006).

Life cycle assessment is a methodological tool used to quantitatively analyze the life cycle of products/activities within the context of environmental impact. The application of this tool underwent major changes during the 1990s. It was initially developed to clearly compare defined end product alternatives, such as various forms of milk packaging or baby diapers. However, it has been rapidly incorporated into higher strategic levels, including decision-and policy-making at firm/corporate levels. Life cycle assessment is currently used for assessing a wide range of products and activities, from ecolabeling to product design as well as energy systems, food production, and transportation alternatives; at present, it clearly extends beyond an assessment of end products (ISO 14040).

The domain of the studied pathway is cradle to grave. The functional unit under study consists in a Cuban local biodiesel plant (located in the central region) with a capacity of 105 600 *L/yr* (400 *L/d*) and 264 working *d/y*. The land use is 32.7 *ha/yr* (30%), 1333 *tree/ha*. *J*CL oil has conventional production conditions (Machado and Suárez 2009; Sotolongo 2007). The activities for every stage of production's life cycle of biodiesel from *J*CL oil are shown in Figure 1.

The assessment will be done by means of the four stages of LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation (Contreras et al. 2009).

Goal and scope definition

LCA studies incorporate resource consumption, energy balance, and emissions throughout various stages of the process within the system boundary. The assessment is done by means of Life Cycle Assessment, according to the ISO 14040 series by using the SimaPro 6.0 LCA software, Ecoinvent database, and the Eco-indicator 99 methodology.

The main goal of this investigation is to identify, quantify and compare the environmental impact categories of biodiesel production from *J*CL oil.

Figure 2 shows the system boundary adopted in this study. The by-products of the life cycle of *J*CL oil are sorted into stages: those that are originated during the agriculture stage and those that are formed during the industrial process.

Inventory analysis

The inventory process requirements were selected and then normalized to a functional unit of 400 *L/d* (12.23 *L/d-ha*). The numerical figures used in the base case study are shown in Table 1. This data inventory considers energy, mass flows, and transportation within the defined system boundaries. Each of these stages is characterized by energy requirements which appear as heat (expressed in *MJ*) or electricity (expressed as *kWh*).

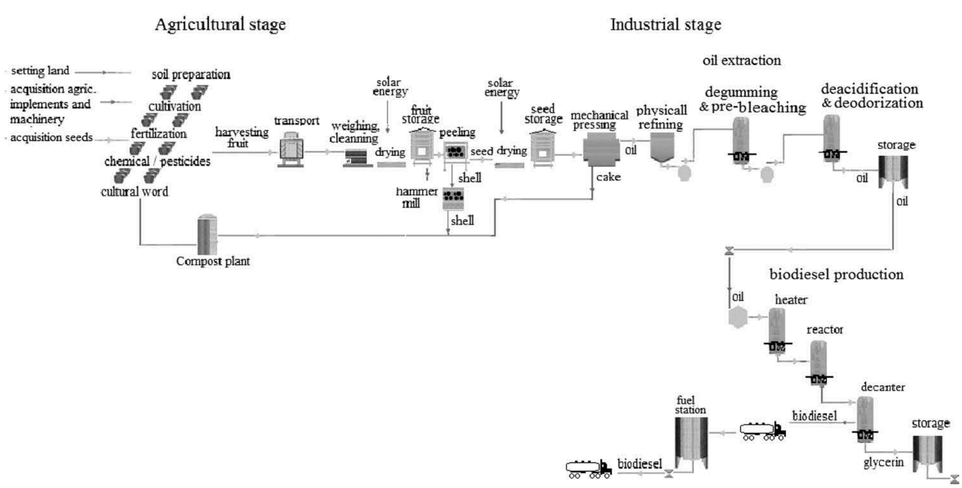

Figure 1. Processes involved in a biodiesel plant (Own proposal).

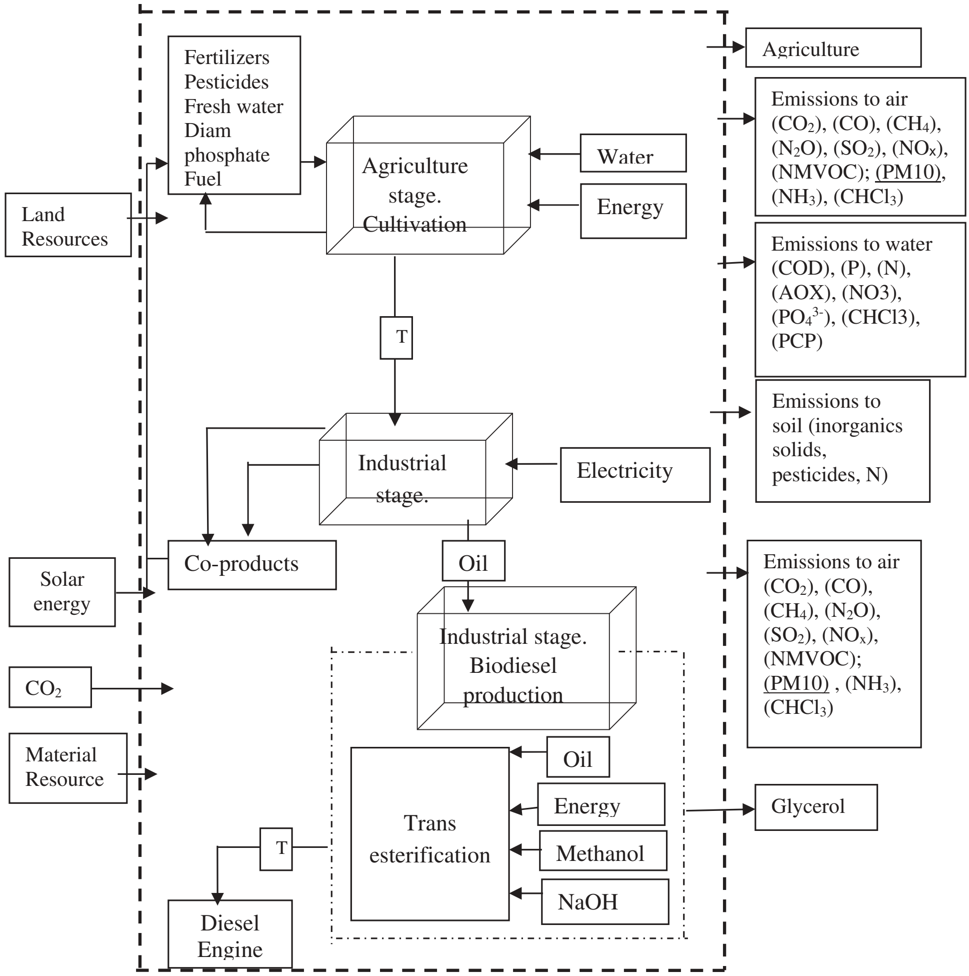

Figure 2. System boundary and process description of the studied *Jatropha curcas* L biodiesel model Inventory analysis.

Data (fertilizer, water, pesticides, etc.) used for modeling in this study were collected from a wide review of literature (Al Basir, Datta, and Kumar 2015; Al Basir, Venturino, and Kumar 2016; Achten et al. 2010; Ajayebi, Gnansounou, and Raman 2013; Berchmans and Hirata 2008; Demirbas 2008; Roy et al. 2014; Marchetti, Miguel, and Errazu 2005; Pandey et al. 2012; Toral et al. 2008; many others) and normalized for 400 *L/d* biodiesel produced.

1 - Sotolongo (2007). 2- Machado and Suárez (2009). 3- Toral et al. (2008). 4- Ajayebi, Gnansounou, and Raman (2013). 5- Achten et al. (2010). 6- Gumnder et al. (2012). 7- Kumar et al. (2012). 8- Contreras et al. (2009).

Results and discussion

Impact assessment

The processes were designed for the conditions required by this case study. The impacts were calculated based on the Ecoinvent database 2003 and the method eco-indicator 99, Pré Consultans 2004, summing up the contributions of all inventory compartments within a defined impact category by considering the conditions that were described above. The Hierarchist perspective was considered, as a reference, based on the most common policy principles regarding time-frame (Gumnder

Table 1. Data inventory of biodiesel production from *Jatropha curcas L* oil for 400 *L/d*.

AGRICULTURE STAGE	INPUT	Water	132.84	L/d-ha	3,4,5.6,7
		Diammonium phosphate (potassium chloride/ triple superphosphate)	1.83	kg/d-ha	3,4,5.6,7
		Urea	3.14	kg/d-ha	8
		Diesel fuel	24.00	L/d	1,2
		Pesticides	0.05	kg/d-ha	3,4,5.6,7
		Solar energy use	2122609.32	GJ/d	8
		Transport from farm to biodiesel plant	40	km	1,2
	OUTPUT	Seed	53.70	Kg	1,2
		Energy from biomass combustion	175.97	MJ	3,4,5.6,7
	EMISSION	N_2O	0.0156	kg/d	8
		N_{total} to water	0.0011	kg/d	8
		Pesticides to water	0.048	kg/d	8
		Pesticides to soil	0.953	kg/d	8
INDUSTRIAL STAGE OIL EXTRACTION	INPUT	Seed	53.70	kg/ha	1,2
		Heat	36.330	MJ	3,4,5.6,7
		Electricity	2.202	kWh	3,4,5.6,7
		Water	0.645	L/d	3,4,5.6,7
	OUTPUT	Oil	15.70	L/d	1,2
		Seed coat, husk and seed cake for fertilizer	37.59	kg/d	1,2
INDUSTRIAL STAGE BIODIESEL PRODUCTION	INPUT	Oil	15.70	L/d	1,2
		Methanol	1.868	L/d	3,4,5.6,7
		Sodium hidroxide	0.157	kg/d	3,4,5.6,7
		Electricity	0.502	kW h	3,4,5.6,7
		Heat	68.502	MJ	3,4,5.6,7
		Water	2.273	L/d	3,4,5.6,7
		Transport-biodiesel plant to clients	80.00	km	1,2
	OUTPUT	Biodiesel	12.23	L/d-ha	1,2
		Glycerin	1.382	kg/d	1,2
INDUSTRIAL STAGE	EMISSION	to air (PM-10, Nitrogen oxides, HC, CO, CO_2, SO_2, NOx)	0.2613	kg/d	8
		to water (wastewater, inorganic solids, total nitrogen, chemical oxygen demand, total phosphorus)	91.8826	kg/d	11
		to soil (filter cake)	0.44134	kg/d	8

Table 2. Overall results for 11 environmental impact categories, Biodiesel model, given in Eco-points.

	total	Agriculture stage	Industrial Stage total	Industrial stage extraction	Industrial stage production
Ozone layer depletion	−0.18	−0.35	0.17	0.04	0.13
Climate change	298.64	281.41	17.24	4.39	12.85
Radiation	6.18	9.29	−3.10	−1.10	−2.00
Respiration – organics	3.22	2.82	0.40	0.14	0.26
Respiration – inorganics	22050.91	361.63	21689.28	1182.07	20507.21
Carcinogens effect	−621.51	−345.75	−275.77	−97.76	−178.01
Subtotal Human health	21737.26	309.05	21428.22	1087.78	20340.44
Land use	24303.59	26274.61	−1971.02	−1290.03	−680.99
Acidification/eutrophication	98.00	−3880.51	3978.51	1398.94	2579.57
Ecotoxicity	−262.64	−119.05	−143.58	−50.90	−92.68
Subtotal Ecosystem quality	24138.95	22275.05	1863.91	58.01	1805.90
Fossil fuels depletion	1335.40	2427.22	−1091.82	−277.87	−813.95
Minerals	534.16	610.44	−76.28	−11.79	−64.49
Subtotal Resources	1869.56	3037.66	−1168.10	−289.66	−878.44
Total	47745.77	26140.8	21604.96	7658.96	13946

Table 3. Overall results for 11 environmental impact categories, given in DALY, PDF*m^{2}yr, PAF*m^{2}yr, and MJ surplus.

Ozone depletion	DALY	−0.00001
Climate change	DALY	0.01146
Radiation	DALY	0.00024
Respiration – organics	DALY	0.00012
Respiration – inorganics	DALY	0.84679
Carcinogens	DALY	−0.02387
Land use	PDF*m^{2}yr	311584.48
Acidification/eutrophication	PDF*m^{2}yr	843,76
Ecotoxicity	PAF*m^{2}yr	−33671.96
Fossil fuels	MJ suplus	56109.53
Minerals	MJ suplus	22446.19

et al. 2012). The next mentioned potential impacts (Table 2 and Table 3) have been normalized by the EDIP method, using the world and European normalization references, representing the annual average impact from an average citizen-a person equivalent, PE.

+, harmful, -, favorable

Interpretation

The interpretation includes an assessment of the significant inputs, outputs, and methodological choices in order to understand the results. This way, the life cycle interpretation phase, in this case, comprises the analysis of the following elements (see Table 2).

Damage category human health

Ozone layer. The result is favorable. Photochemical ozone formation in harvesting is an activity with a very low contribution as there is no burning in harvesting and there is little emission from non-biodiesel use.

Climatic change. The processes that involve fossil fuel use and electricity generation are reduced due to the low electricity consumption and mainly because of the use of biodiesel instead of petroleum in trucks for transportation, tractors for harvesting, and other transport services, all these lead to some impact reduction in this category.

Radiation. The result is not significant.

Respiratory effects of organic compounds. The small contribution is due to the use of biodiesel substituting petroleum for transport purposes. The results prove that the substitution of these products decreases the risk of suffering respiratory diseases.

Respiratory effects of inorganic compounds. These are related to particles (PM 2.5 and PM 10), nitrogen oxides and sulfur dioxide. A contribution to this category is not high due to the use of the produced biodiesel as fuel. Particle emission occurs although the emission of organic substances is avoided.

Carcinogens. The results in this category are associated with the emission reduction of organic compounds into air, water, and soil. The alternative shows favorable results due to the use of liquid and solid wastes. The filter cake and waste-water are used for fertilization. Besides, the used biodiesel does not contain benzene or other carcinogenic aromatic substances (polycyclic aromatic hydrocarbons) and, as a vegetal substance, does not contain any substance harmful to health.

Damage category ecosystem quality

Land use. This is the most significant category. Land use can hardly be reduced only by higher production efficiency. The applicated eco-indicator tool shows that land use is heavily weighted as an impact category.

Acidification-eutrophication. It is due to inorganic compounds'emissions from fertilizer production processes and use, electricity generation and diammonium phosphate use. The acidification impact potential is mostly due to the NOx emitted by biodiesel combustion due to the use of sulfuric acid in the industrial process.

Ecotoxicity. The favorable results are due to the use of electricity from biomass combustion and the use of agriculture waste. No chemical emissions are recorded for unit processes. For the other processes, the main contributions to the ecotoxicity impact potential come from the chemical applications during crop growth, because of the low quantity of applied pesticides. The terrestrial toxicity potentials are low because of the assumption that the field is considered part of the technosphere and the emissions from the field to the surrounding environment are unknown.

Damage category Resources

Fossil fuels. The impact into this category is generally dominated by the petroleum consumption. They are involved in most of the analyzed processes. However, in this case, there is a good result because of the substitution of diesel fuel by biodiesel.

Minerals. This production does not require a high amount of minerals. A non considerable number of minerals have been used as raw material in this process. There are no other processes as biogas and alcohol production that use higher quantities of minerals.

DALY, Disability-Adjusted Life Years.
PDF*m^2yr, Potentially Disappeared Fraction of species.
PAF*m^2yr, Potentially Abiotic depletion Factor
MJ surplus,

Conclusions

Table 2 summarizes the ecopoints into three damage categories: human health, ecosystem quality, and resources, and for each impact category. A difference between the three categories: 21737.25, 24138.95, 1869.55 ecopoints was observed. Globally, impact on human health is observed, due to a certain level of respiratory effects of inorganic emissions. The most significant difference is in ecosystem quality impact because of the land use. Finally, an improvement concerning land use impact and an appropriate implementation for using wastes and by-products of the process, in order to reduce fertilizer and fossil fuel consumption is suggested.

Acknowledgements

The authors wish to express their thanks to the Flemish Interuniversity Council's (VLIR) University Development Cooperation, funding an Own Initiatives Program entitled "Knowledge cell on biofuels (from non-edible crops and waste products) for use in internal combustion engines" and a South Initiatives Program entitled "Emulsified systems for biofuels. Assessment of their performance in diesel engines". Thanks to the VLIR support much of this research was performed.

Funding

This work was supported by the Flemish Interuniversity Council's (VLIR) University Development Cooperation, funding an Own Initiatives Program entitled "Knowledge cell on biofuels (from non-edible crops and waste products) for use in internal combustion engines" and a South Initiatives Program entitled "Emulsified systems for biofuels. Assessment of their performance in diesel engines".

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