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ORIGINAL PAPER

Life cycle assessment of *Jatropha curcas* biodiesel production: a case study in Mexico

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Abstract
The potential of liquid biofuels (like bioethanol and biodiesel) to reduce greenhouse gas (GHG) emissions from the transportation sector has generated a great deal of interest in the last few years, with particular attention being given to Jatropha methyl ester (JME). *Jatropha curcas* (Jc)—a species native to Mexico—shows some promise as a source of oil for biodiesel. A few studies on biodiesel production from Jc have been conducted in Mexico, but just one study involved a life cycle assessment (LCA) of JME. At the international level, most studies dealing with Jc focus on the biodiesel industrial process, while in this paper we also look in detail at the agricultural production phase. This case study provides preliminary results on GHG emissions and energy balances of JME production in Mexico, applying the LCA methodology recommended by the European Renewable Energy Directive (RED). Four production systems (JME 1–4) were studied, resulting in GHG mitigation of between 41 and 53% with regards to diesel if no direct land-use change (dLUC) change occurs. However, when accounting for GHG emissions arising from direct land-use change (dLUC), total emissions increase from 40 to 508 kg CO_2e/GJ. The differences between dLUC on tropical dry forest and dLUC on grassland are of lesser importance than those between systems with and without dLUC. Using JME from plantations on lands, previously not cultivated, leads to GHG emissions three or six times higher than using fossil diesel. These results are an approximation to the environmental and energetic impacts of JME production in Mexico. Further studies should be performed before implementing more plantations to produce biofuel from *J. curcas*.

Keywords *Jatropha curcas* · Biodiesel · GHG emissions · Energy balance · Life cycle assessment

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Introduction

Our strong dependence on fossil fuels to satisfy energy needs has resulted in important environmental issues at the global level (e.g., change in global climate) and prompted the development of energy policies directed to switch from fossil to renewable energy sources. In Mexico in 2016, total energy consumption was 5479 Petajoules (PJ); the transportation sector accounted for 47% (2284 PJ), where fossil fuels accounted for more than 99% of this share, mainly gasoline (65%) and diesel (26%) (SENER 2017).

First-generation liquid biofuels have been considered as an interesting alternative to decrease oil dependence of the transport sector; however, this option requires the use of cultivable land to harvest crops, which can be processed into biofuels. The controversy surrounding the social and environmental impacts of biofuel production is a central issue regarding their sustainability (Robledo-Abad et al. 2017; Dale et al. 2013; Ruiz-Mercado et al. 2013; Mata et al. 2011). In order to be truly sustainable, biofuels should be (among other things) an effective alternative to mitigate GHG emissions, should have an Energy Return on Investment (EROI) greater than one, and should not compromise food security.

In the case of biodiesel production, *Jc* appears to be a promising crop: most varieties are not edible (Mexico has both toxic and non-toxic varieties); it grows on poor and degraded soils and requires little water and other agricultural inputs in order to produce fruit (Blanco-Marigorta et al. 2013; Francis et al. 2005; Jongschaap et al. 2007; Achten et al. 2008; Kumar and Sharma 2008). The State governments of Veracruz, Puebla, Morelos, Chiapas, Nuevo León, Michoacán, Mexico and Sinaloa, as well as some federal policies, have provided financial support for plantations of *Jc;* however, there exist few experimental data regarding cultivation practices, few detailed analyses on energy consumption and GHG emissions, and little knowledge on the use of the byproducts of oil extraction.

While there are some environmental impact studies based on LCA of JME from Thailand (Prueksakorn and Gheewala 2006, 2008; Sampattagul et al. 2007), India (Tobin 2005; Achten et al. 2010; Reinhardt et al. 2007), China (Ou et al. 2009), West Africa (Ndong et al. 2009), and Malaysia (Lam et al. 2009), a few studies have been carried out in Latin America. Skutsch et al. (2011) examined some social and environmental aspects of *Jatropha curcas* production in three states of Mexico and estimated the time needed to offset GHG emissions due to dLUC in a case study in Yucatan, but there is just one article on the LCA of JME in the country (for Yucatan, Sacramento-Rivero et al. 2016).

Biofuels are discussed as a low-carbon alternative to fossil fuels. In the context of global efforts to mitigate climate change, like the United Nations climate change conferences in Paris in 2015 and Bonn in 2017, GHG savings were identified as the most important criterion, biofuels have to fulfill. At a country level, the promotion of liquid biofuels in Mexico is a relatively recent policy, structured upon the Law for the Promotion and Development of Biofuels (LPDB) and the Program for the Introduction of Bioenergy established by the Intersectoral Bioenergy Strategy. Both documents target reduction of GHG emissions and favorable energy balances as central sustainability criteria for biofuels (LPDB 2008; SENER 2008a, b). However, there are just a few studies on the GHG balance of biodiesel from *Jc* to inform policymaking.

This study aims to apply LCA to calculate energy balances and GHG emissions of JME in Mexico in order to provide more information on the environmental and energy aspects of the possible biodiesel production form *J. curcas*. Other parameters, which are of importance to assess JME's environmental (and social) sustainability, are beyond our study's scope.

Methodology

LCA allows for the calculation of net exchange in energy inputs and outputs resulting from the use of biofuels, and GHG emissions attributed to each production unit (Kammen et al. 2008). There are various software options available to perform LCA: GREET (ANL 2008), EBAMM (CU Berkeley 2008), RTFO (Bauen et al. 2008), SenterNovem (Hamelinck et al. 2008), HGCA (Woods et al. 2005), but they do not have a database for Mexico.

We opted for the methodology recommended by the Renewable Energy Directive (RED) of the European Union Parliament (EUC 2009), following ISO 14040-44 guidelines (ISO 2006a, b). The inputs/outputs measurements were carried out until biodiesel is mixed with diesel in a Mexican refinery. Our analysis is referred to as "well to refinery" and includes four phases: (a) agricultural (or raw material production); (b) oil extraction from the seeds (first industrial phase); (c) transesterification of the oil (second industrial phase); and (d) transport, which includes transport of raw material for processing, intermediaries and final transport to refineries (Fig. 1).

Systems studied

In the production of JME, two co-products are generated that can be re-used in the process: press-cakes to substitute chemical fertilizers, and fruit husks to replace fossil fuel. Also, several land-use changes are possible. We analyze four systems (see Table 1), differing in:

(a) *The type of fertilizer applied* Chemical fertilizer, mixture of press-cake and chemical fertilizer

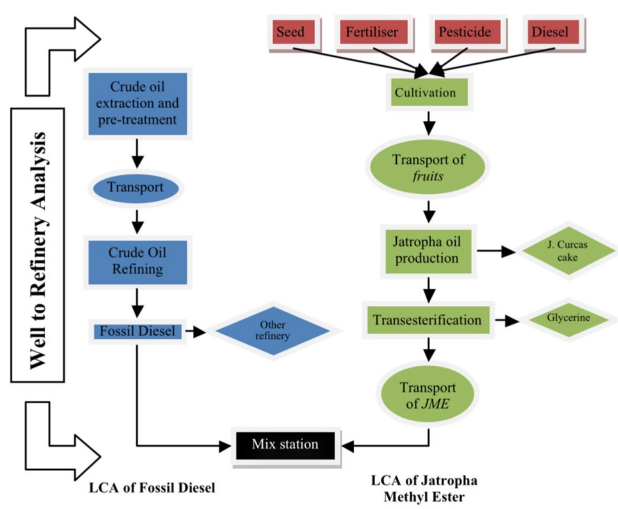

Fig. 1 Life cycle tree for fossil diesel and biodiesel

Table 1 Systems analyzed for biodiesel production in Mexico

System	JME1	JME2	JME3	JME4
Fertilizer	Press-cake	Press-cake	Chemical fertilizer	Chemical fertilizer
Fuel used in industrial phase	Husk	Fossil fuel	Husk	Fossil fuel
dLUC	Dry forest, grassland	Dry forest, grassland	Dry forest, grassland	Dry forest, grassland

(b) *Fuel used in the industrial phase for process heat generation* Fossil fuel or biomass (*Jc* byproduct: fruit husk)
(c) *Direct land-use change* From tropical dry forest or grassland.

Functional unit

The functional unit must be clearly defined, quantitatively measurable, and consistent with the study's objectives and scope (ISO 2006a, b; Lechón et al. 2006), to allow a clear comparison between different systems with a common base. Since the system's function is to produce biofuel in order to replace fossil fuel for diesel motors, the functional unit is defined as 1 Gigajoule of energy delivered at a refinery (Achten 2010; Gnansounou et al. 2009; Bailis and Baka 2010; Ndong et al. 2009; Cherubini and Strømman 2011). A focal impact category is the emission of GHG, calculated as CO_2 equivalent and expressed in kg $CO_2e/GJ_{biodiesel}$. This is consistent with RED criteria (EUC 2009). In order to measure the energetic impact, we used the $GJ_{fossil\ input}/GJ_{biodiesel}$ relationship (Fossil Energy: Renewable energy), and EROI.

Limits of the system and indices of performance

In the case of fossil diesel, we excluded the emissions and energy use associated with the production of the machinery and infrastructure necessary for extraction, transport and refinement of crude oil; this is consistent with other studies, and according to DeLuchi (1991), this contribution in the global energy balance is limited. The emissions and energy due to the manufacture of agricultural machinery, transport vehicles and equipment and installations for the extraction of oil and its conversion into biodiesel were also excluded. The GHG taken into consideration in all phases are CO_2, CH_4 and N_2O, with a global warming potential of 1, 23 and 296 respectively (IPCC 2001). For the "well to refinery" analysis, JME was compared to Mexican fossil diesel. The reference emission value (84.2 kg CO_2e/GJ) for fossil diesel was obtained from the PEMEX oil refinery in Tula, Mexico (Gasca 2010, personal communication and data file access).

The energy balance allows the calculation of the ratio between fossil fuel energy and renewable energy: (FE/RE), expressed as $GJ_{fossil\ input}/GJ_{biodiesel}$. We also calculated EROI based on the ratio: $GJ_{biodiesel}/GJ_{fossil\ input}$ (Murphy and Hall 2010; Shie et al. 2011; Solomon 2010; Mulder and Hagens 2008).

Agricultural process

The systems are based on one case study in Parácuaro, Michoacán, with an estimated yield of 1.7 t_{fruit}/ha (or 1.1 t_{seed}/ha^{-1}). This plantation was irrigated by gravity, applying 2580 m^3 ha^{-1} year^{-1}. The trees were planted at 2.5 m × 2.5 m spacing (approximately 1600 plants ha^{-1}). Land preparation for cultivation was done with a tractor, while harvest and fruit loading were manual. Seed production in the first year was practically zero, and reached 600 kg ha^{-1} in the second year. As this study was undertaken in the third year (and lacked production data for that year), we extrapolated for 20 years, estimating a yield of 1.1 t_{seed} ha^{-1} year^{-1} as an average, based on data obtained from international sources (Sacramento-Rivero et al. 2016; Edrisi et al. 2015; Van Eijck et al. 2014; Singh et al. 2014; Kant and Wu 2011; Trabucco et al. 2010).

Although chemical fertilizer was not used until the second year in this plot, we assumed that to guarantee a consistent yield over the long-term, it was necessary to replace the nutrients exported with the fruits. A Nutriment Replenishment Rate (NRR) of 1:1 was applied to all systems, replacing N:P:K at the rate of 38:15:42 kg/ha*year. The nutrient content of the fruits was obtained from previous research (Reinhardt et al. 2008). However, considering it to be highly probable that the crop will use only 50% of the nutrients applied to the soil (FAO 2001), we also compared two ratios of NRR (1:1 and 2:1), along with the impact of dLUC.

The data regarding inputs used in this plot (work, agrochemicals and fuels) were collected directly from the owner. The energy equivalent and CO_2 emissions were obtained by stoichiometry and from coefficients. N_2O emissions were estimated by the volatilization of nitrogenous fertilizers and combination of fertilizer and press-cake. Furthermore, we calculated the emissions generated and energy consumed in the production of fertilizers and pesticides, as well as emissions and energy corresponding to the use of fossil fuel in the agricultural machinery.

Industrial phase

The industrial phase of biofuel production was divided into oil extraction and transesterification. Both occur in the same place, so there is no need for transportation between sites. In both stages we took into account the use of electric and thermal energy (heat/steam). The chemical inputs in the transesterification stage were methanol as a reactant and sodium hydroxide as a catalyst. Electricity for the refining of glycerine was also included. The assumed conversion rate for the transesterification reaction was 99%.

Oil extraction process This stage considered the emissions and energy expenditure generated by the fuel in the boilers, which produced thermal energy and electricity used in this stage. A resulting byproduct was generated (press-cake) that can be used as organic fertilizer.

Transesterification of the oil The oil has low acidity and does not require pre-esterification before the usual transesterification process (Blanco-Marigorta et al. 2013).

Transesterification is the most common way to produce biodiesel (Encinar et al. 2005). Vegetable oil (triglyceride) reacts in the presence of a catalyst with a primary alcohol to give the corresponding alkyl esters of the fatty acids [Ahn et al. 1995; Kiss 2014; Santacesaria et al. 2012 (as cited in Neumann et al. 2015); Dhar and Kirtania 2009]. Most biodiesel production processes use excess methanol to get high yield, therefore a methanol recovery unit is necessary to avoid high energy and economic costs (Pleanjai and Gheewala 2009).

Biodiesel production by transesterification requires several expensive downstream processing steps like, the purification of biodiesel, as well as the separation of excess methanol, glycerol and water (Dunford 2007; Fjerbaek et al. 2009; Helwani et al. 2009; Atadashi et al. 2011 as cited in Kiss and Ignat 2012). A technology, which facilitates the purification of biodiesel, is reactive distillation (Pérez-Cisneros et al. 2016; Kiss and Ignat 2012). During reactive distillation, two processes take place within the same unit operation: (1) the transesterification reaction, and (2) the separation of subsequent products (Poddar et al. 2015). Based on the applied separation technology it can be used in combination with reactive extraction and reactive adsorption (Shinde et al. 2011). Data were taken from international references of IFEU (calculator) with their respective reaction conditions and transesterification technology. GHG emissions are due to the fuel used by the boilers and electricity consumed in the process.

Transport

Transport refers to the fruit's movement from the cropping areas to the industrial plant, and the JME to the refinery. We estimated the average distances for both and calculated GHG emissions and energy expenditure for diesel trucks. The average distance of transport from the fields to the industrial plant was 170 km (round trip). The distance between the industrial plant and refinery was 340 km. In the systems where the residual press-cake was evaluated as organic fertilizer (JME1 and JME2), emissions generated and energy consumed by the transport of the residual press-cake from the industrial plant to the field were calculated in the same way.

Direct land-use change (dLUC)

When crops are established in soils with forest cover, emissions due to dLUC arise from the liberation of carbon previously stored in vegetation and soils. The amount of carbon stored in biomass and soil depend on the vegetative cover. We used data from the National Inventory for Emissions of Greenhouse Gases (INE 2006), to assess carbon stocks in natural grasslands, tropical dry forest, and agricultural areas.

Another type of emission may be generated (named emissions from indirect Land-use Change), if a plantation is made in an area previously used for agriculture and this crop is displaced to another land, originally not allocated for that purpose. This indirect emission potential must be modeled separately and added to the total emission potential.

In this study we analyzed dLUC impact, assuming the extension of *Jc* plantations in areas not currently used for agriculture, i.e., planting on grasslands and tropical dry forests. In both cases, average carbon content values (tC/ha) were those reported by INEGEI, 2006 (INE 2006) (Table 2). While these values have a high level of uncertainty, they are the best estimates currently available for Mexico. The calculated emissions due to dLUC are annualized over 20 years, as suggested by the RED.

Table 2 Carbon above and below ground and in soil for land use change calculations. *Source*: [a]Kant and Wu (2011); [b]Author calculation

		Previous use		Use
		Grassland[a]	Dry forest[a]	*J. Curcas*[b]
Carbon content, total	t C/ha	95.4	89.3	60.4
Carbon in biomass above + below ground	t C/ha	34.2	21.6	3.6
Organic soil carbon	t C/ha	61.2	67.7	56.8

We assume that all the carbon lost by dLUC converts into CO_2, using the Eq. (1),

$$\text{Emissions}_{\text{dLUC}} = \frac{\left(\left(C_{\text{BU}} - C_{\text{AU}}\right) \times 3.67 \frac{\text{kg}\,CO_2}{\text{kg}\,C}\right)}{20} \quad (1)$$

where C_{BU}, Carbon in soil from previous use; C_{AU}, Carbon in soil of alternate use; 20, annualized over 20 years.

Treatment of byproducts (allocation of emissions, byproduct use)

Most production processes for biofuels generate byproducts—e.g., glycerin, residual press-cake—which can be used as forage, organic fertilizer and/or biofuel. If this happens, the energy consumed and emissions generated by the production process should be offset by the energy and emissions recovered in the products and byproducts (Biofuels UNEP 2009; ISO 2006b). There are basically two ways to treat byproducts: (1) by substitution or expansion of the system and (2) by allocation (Bauen et al. 2008). The allocation method can be implemented in relation to market prices, energetic content, or mass.

According to the ISO 14041 guidelines, the allocation model should be avoided, if possible, by expanding the system to include additional functions related to the byproducts (Jungbluth et al. 2007; ISO 2006b; Panichelli et al. 2008; Vikman et al. 2004; Börjesson 2009).

The system's expansion requires information regarding the substituted products, since the clear implication is that the byproducts have potential market value (Biofuels UNEP 2009). This method attributes the environmental impact, which would correspond to the byproduct, and shows the potential environmental impacts, resulting from an alternate system where the given service is provided by the byproduct (Lechón et al. 2006). While this method is recommended by ISO standards (ISO 2006a, b), there are a number of issues regarding the products it would substitute, since it itself requires previous LCA. Moreover, it is possible that a given byproduct can substitute for more than one product and it would be necessary to determine which substitution (if any) would be viable. This allocation method is based on the logic that production is guided by market price (both of the product and byproduct). The disadvantages of this method have been discussed by Börjesson (2009) in reference to the price fluctuation over time that then relegates the allocated emissions strongly, as defined by variation in the market for the product at any given time.

Allocation by mass and energy contents account for physical properties: (a) by mass content according to the relative masses of biofuels and co-products (García et al. 2011); (b) by energy content allocating emissions (or energy) in accordance with the energy content of biofuels and byproducts.

Each of the three approaches has advantages and disadvantages. Since they also generate different results regarding GHG and energy balances, there is scientific debate about which is the most appropriate. The European Union has decided to use the allocation by energy content as it is considered a more accurate and robust approximation and uses empirical coefficients, proven and available (Fehrenbach et al. 2008). It is this approach, we used for this study.

As the press-cake contains nutrients, it can be used as fertilizer (Bailis and Baka 2010). In JME 1 and JME 2, we assumed it is all used within the same system, as partial biofertilizer for the crop; thus, the press-cake is not considered a byproduct and LCA emissions are allocated exclusively to biodiesel and glycerin.

In JME3 and JME4, press-cakes leave the system as a byproduct to be used as animal feed, and the emissions are allocated by the energetic content of JME and the byproduct. It is assumed that the press-cake can be used as animal feed, as it comes from non-toxic varieties of *Jatropha*, and contains a great deal of crude protein (Makkar et al. 1998). In these systems, the allocation to byproducts lowers the emissions from biodiesel.

When the byproduct is not used, the distribution of emissions is similar for all systems: those from dLUC, cultivation and transport of fruits are transferred completely to biodiesel, while those in the category of transesterification are assigned 98.3% to biodiesel and 1.7% for glycerin.

In order to get a base for allocation calculations, we calculated the mass flow of Fig. 2, showing the kilograms of each one of the products and byproducts corresponding to 1 GJ of biodiesel (the system's functional unit).

Inventory analysis

We collected the data for these analyses in situ. The inventory analysis and the model, we used to calculate GHG emissions and energy balance for the life cycle were completed using a spread sheet model based on the RED methodology used in other LCA. This model, previously developed by the IFEU (Fehrenbach et al. 2008), was adapted for our study in Mexico. We aggregated additional modules for the calculation of total primary energy, non-renewable energy, emissions related to dLUC and emissions resulting from the use of electricity (Table 3).

We obtained data inputs regarding cultivation (fuels, agrochemicals) at a farm in Parácuaro, Michoacán, through direct interviews/surveys. The energy equivalents and CO_2 emissions were obtained using energy coefficients and theoretical stoichiometric yields. The energy requirements for fabrication of fertilizers were also accounted for. The fruit husk was considered a byproduct of the oil extraction, used

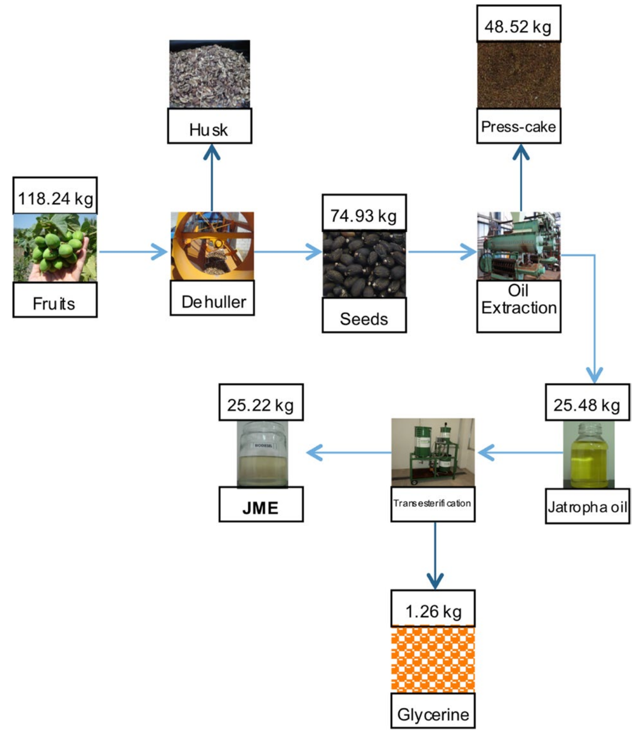

Fig. 2 Mass flow for 1 GJ from biodiesel

to generate energy and heat (Vyas and Singh 2007; Gübitz et al. 1997; Bailis and Baka 2010; FACT 2009; Achten et al. 2008). The N_2O emissions resulting from volatilization of nitrogenous fertilizers were estimated according to IPCC guidelines (IPCC 2006a, b).

Emission factor for electricity from the national electricity system

In Mexico, electricity is largely produced from fossil fuels. The average emission factor obtained from the National Electric System (NES) was 498 gCO_2e/kWh (Table 4). The total energy efficiency calculation was 39.5%, and the fossil fuel energy efficiency value was 40.7%.

Results and discussion

GHG emissions

Land-use change (dLUC)

Without taking dLUC into account, all systems achieve reductions of GHG emissions compared with the fossil reference ranging from 41% (when emitting 50.07 kg CO_2e/GJ) to 53% (when emitting 39.68 kg CO_2e/GJ) (Table 5). However, with the inclusion of emissions from dLUC, the emissions from JME were much greater than those referenced for fossil fuel (84.2 kg CO_2e/GJ): higher by 191% (160.54 kg CO_2e/GJ) for JME3 in the tropical dry forest, and higher by 467% (393.17 kg CO_2e/GJ) in JME2 on grassland. This indicates that expanding cultivation into previously uncropped areas of high carbon density has a high, negative environmental impact, even annualizing these carbon emissions over 20 years. The differences between dLUC on tropical dry forest and on grassland are of much lesser importance than those between systems with and without dLUC.

Agricultural phase

The main variables causing GHG emissions are volatilization of N_2O and production of fertilizers and pesticides. Where the press-cake is used as fertilizer (JME1 and JME2), the biggest emissions were due to volatilization of N_2O with 7.8 kg $CO_2e/GJ_{biodiesel}$ (44%), followed by the use of pesticides and herbicides with 5.1 kg $CO_2e/GJ_{biodiesel}$ (29%), direct application of fertilizers with 3.9 kg $CO_2e/GJ_{biodiesel}$ (23%) and the use of diesel with 0.7 kg $CO_2e/GJ_{biodiesel}$ (4%). In the other systems, the greatest emissions resulted from the production of fertilizer: 11.2 kg $CO_2e/GJ_{biodiesel}$ (52%), followed by volatilization of N_2O with 6.9 kg $CO_2e/GJ_{biodiesel}$ (32%), pesticides and herbicides with a value of 2.9 kg $CO_2e/GJ_{biodiesel}$ (14%) and diesel use with 0.4 kg $CO_2e/GJ_{biodiesel}$ (2%).

The production of fertilizer, as well as volatilization of N_2O were critical variables in the agricultural phase: (a) if the press-cake is partially used as fertilizer, this byproduct remains in the production system and reduces emissions by 15.5 kg $CO_2e/GJ_{biodiesel}$ (−80%) and 4.1 kg $CO_2e/GJ_{biodiesel}$ (−34%) by N_2O volatilization; (b) if the press-cake is not used as fertilizer, it leaves the production system as a byproduct and has an emission allocation, resulting in a reduction of 7.2 kg $CO_2e/GJ_{biodiesel}$ (−64%), but on the other hand it raises emissions by 0.9 kg $CO_2e/GJ_{biodiesel}$ (+13%), due to N_2O volatilization from use of chemical fertilizers.

Industrial phase

The final emissions in this phase of production are principally dependent on the fuel used in the plant: JME1 and JME3, which use the fruit husk as fuel, emit 19.6 kg $CO_2e/GJ_{biodiesel}$; but JME2 and JME4, which use fuel oil to produce heat, emit 30.1 kg $CO_2e/GJ_{biodiesel}$. After the emissions allocation, the values for each system were: JME1 19.3 kg $CO_2e/GJ_{biodiesel}$, JME3 16.7 kg $CO_2e/GJ_{biodiesel}$, JME2 29.6 kg $CO_2e/GJ_{biodiesel}$, JME4 23.9 kg $CO_2e/GJ_{biodiesel}$. The emissions in the industrial phase accounted for 49, 59, 42 and 51% of the total emissions for JME1, JME2, JME3, JME4 systems, respectively.

Table 3 Data for the calculation of LCAs for the systems we analyzed

	JME1	JME2	JME3	JME4	Description
Cultivation					
Nitrogen (kg/ha*yr)[a]	5.8		38		Chemical nitrogen
Seedcake-N (kg/ha*yr)[a]	32.2		–		Renewable nitrogen
Phosphate P_2O_5 (kg/ha*yr)[a]	0.6		15		Chemical phosphate
Seedcake-P (kg/ha*yr)[a]	14.4		–		Renewable phosphate
Potassium oxide K_2O (kg/ha*yr)[a]	33.0		42		Chemical potassium
Seedcake-K (kg/ha*yr)[a]	9.0		–		Renewable potassium
Insecticide + herbicide (kg/ha*yr)	6.1				Chemical pesticides
Diesel (kg/ha*yr)	3.0				Land preparation
Irrigation	–				Rainfed agriculture
Yield (t seed/ha*yr)	1.1				Estimated yield
Industrial phase					
Electr. mill (kWh/kg oil)[b]	0.48				Energy for oil extraction
Electr. refining (kWh/kg oil)[b]	0.014				Energy for oil refining
Thermal energy (MJ/kg oil)[b]	2.8				Thermal energy for oil extraction
Thermal energy/refining (MJ/kg oil)[b]	0.303				Thermal energy for oil refining
Electr. mill (kWh/kg JME)[b]	0.42				Energy for transesterification
Thermal Glycerine energy (MJ/kg JME)[b]	1.36				Thermal energy for glycerine processing
Electr. Glycerine-process (kWh/kg JME)[b]	0.29				Energy for glycerine processing
Fuel type in Thermal energy	Husks		Fossil fuel		Renewable fuel/fossil fuel
Auxiliaries					
CH_3OH[b]	10.9% of oil				Methanol/catalyst
NaOH (g/kg)[b]	26				Alkaline-catalyzed transesterification
Transport					
Biomass transport (km)	170				Transportation of *J. C.* seeds
Transport to admixture (km)	340				Transport to refinery

[a]Estimated data based on Jungbluth et al. (2007)

[b]Data from IFEU, based on the assumption that the energy requirements in the industrial phase are comparable

Table 4 Energy balance of electricity and emission factor for Mexico

	Energy input [PJ]	Energy output [PJ]	Efficiency	Total emissions [Mt CO_2e]	Emission factor in energy source[a] gCO_2/kWh
Coal	314.26	112.784	0.36	29.94	**498**
Uranium	114.49	37.516	0.33	–	
Diesel	7.81	2.203	0.28	0.58	
Fuel oil	475.35	168.25	0.35	36.91	
Natural gas	330.25	130.15	0.39	18.54	
Water (hydroelectric)	268.18	97.35	0.36	–	
Endogenous vapor (geothermic energy)	73.43	26.65	0.36	–	
Wind-energy	2.46	0.89	0.36	–	
Diesel + dry gas	531.22	261.39	0.49	29.83	
Total	**2117.45**	**837.19**		**115.81**	
Average			**0.40**		
Fossil fuel	1658.89	674.78	**0.41**		

[a]With total average loss through transmission and distribution of 12% for NES

PJ Petajolue, *Mt* Megatonne

Table 5 Balance of CO_2e emissions for each system analyzed per production phase (annualized for 20 years)

	JME1 kg CO_2e/GJ	JME2 kg CO_2e/GJ	JME3 kg CO_2e/GJ	JME4 kg CO_2e/GJ
Direct land-use change (tropical dry forest)	352.83	352.83	205.06	205.06
Direct land-use change (grassland)	427.30	427.30	248.35	248.35
Production of biomass	17.57	17.57	21.39	21.39
Transport of biomass	1.55	1.55	0.90	0.90
Conversion step I	6.32	13.70	3.75	8.04
Transport of byproduct	0.63	0.63	–	–
Conversion step II	12.97	15.93	12.97	15.93
Transport to fuel storage for admixture	0.67	0.67	0.67	0.67
Total without dLUC	39.72	50.07	39.68	46.93
Reference emission data for fossil diesel	84.2	84.2	84.2	84.2
Balance without dLUC	−44.48	−34.13	−44.52	−37.27
Balance for dLUC in tropical dry forest	308.35	318.69	160.54	167.80
Balance for dLUC in grassland	382.82	393.17	203.83	211.08

BE balance of emissions

Transport

The transport of the fruits causes 2–4% of total emissions. Even if the estimated distance is the same for every system, there is a small difference in the JME1 and JME2 values (1.6 kg $CO_2e/GJ_{biodiesel}$), compared to 0.9 kg $CO_2e/GJ_{biodiesel}$ for JME3 and JME4, due to the allocation from the use of residual press-cake.

The transport of biodiesel from the industrial phase to the refinery with an average distance of 340 km (round trip) generates emissions of low significance, the same for all systems (0.7 kg $CO_2e/GJ_{biodiesel}$) or about 1% of total. The transport emissions of residual press-cake are similar to emissions resulting from the biodiesel transport for JME1 and JME2. If the distances were to be doubled, the resulting values would be around 3% of total emissions.

Total emissions

The total emissions were similar in JME1 and JME3. JME1 showed lower emissions in the agricultural phase (due to the use of the byproduct as fertilizer). However, JME1 did show higher emissions in the transport of biomass and extraction phases. The system which showed the lowest emissions was JME3, in each one of the three phases, due to the allocation to press-cake leaving the system as fodder. In the agricultural phase, the emissions for JME3 totaled 37.4 kg $CO_2e/GJ_{biodiesel}$, but due to the allocation this value drops to 21.4 kg $CO_2e/GJ_{biodiesel}$ (the rest being allocated to the byproducts)—very close to the value for JME1 (17.6 kg $CO_2e/GJ_{biodiesel}$).

Without taking dLUC into consideration, the systems with the lowest emissions were JME3 with 39.6 kg $CO_2e/GJ_{biodiesel}$, and JME1 with 39.7 kg CO_2e/GJ, both lower by 53% than 84.2 kg CO_2e/GJ_{diesel} of fossil diesel. In the first case we assumed the use of press-cake as a partial fertilizer within the system, and in the second case we considered the press-cake as a byproduct exiting the system; notwithstanding that the results are similar. These findings underscore the importance of choosing the allocation criteria, since the reduction of emissions gained by using the press-cake as fertilizer would be equal to the allocation of emissions to the byproduct.

The use of renewable fuel in the industrial phase showed a notable impact on emissions. In the oil extraction stage, the CO_2 emissions resulting from the use of fossil fuel would be reduced by up to 54% when using biomass (fruit husks) as fuel. In the transesterification stage, the reduction is not very high, being around 18% (because the main energy source is electricity).

The emissions attributed to fruit transport, as well as those generated in the transport of biodiesel to the refinery were not significant. Based on these findings, it is advisable to use the fruit husks as fuel in the processing plant in order to lower GHG emissions.

Ratios of nutrient replacement and the impact of dLUC

With NRR of 2:1, the higher use of chemical fertilizers makes the reduction of emissions by JME much less positive: only 4% in JME2 and 31% in JME3 (Fig. 3). It is interesting to note that if the N is replaced in the soil using press-cake as fertilizer, the allocation to byproduct is negated, thus increasing the allocation to biodiesel.

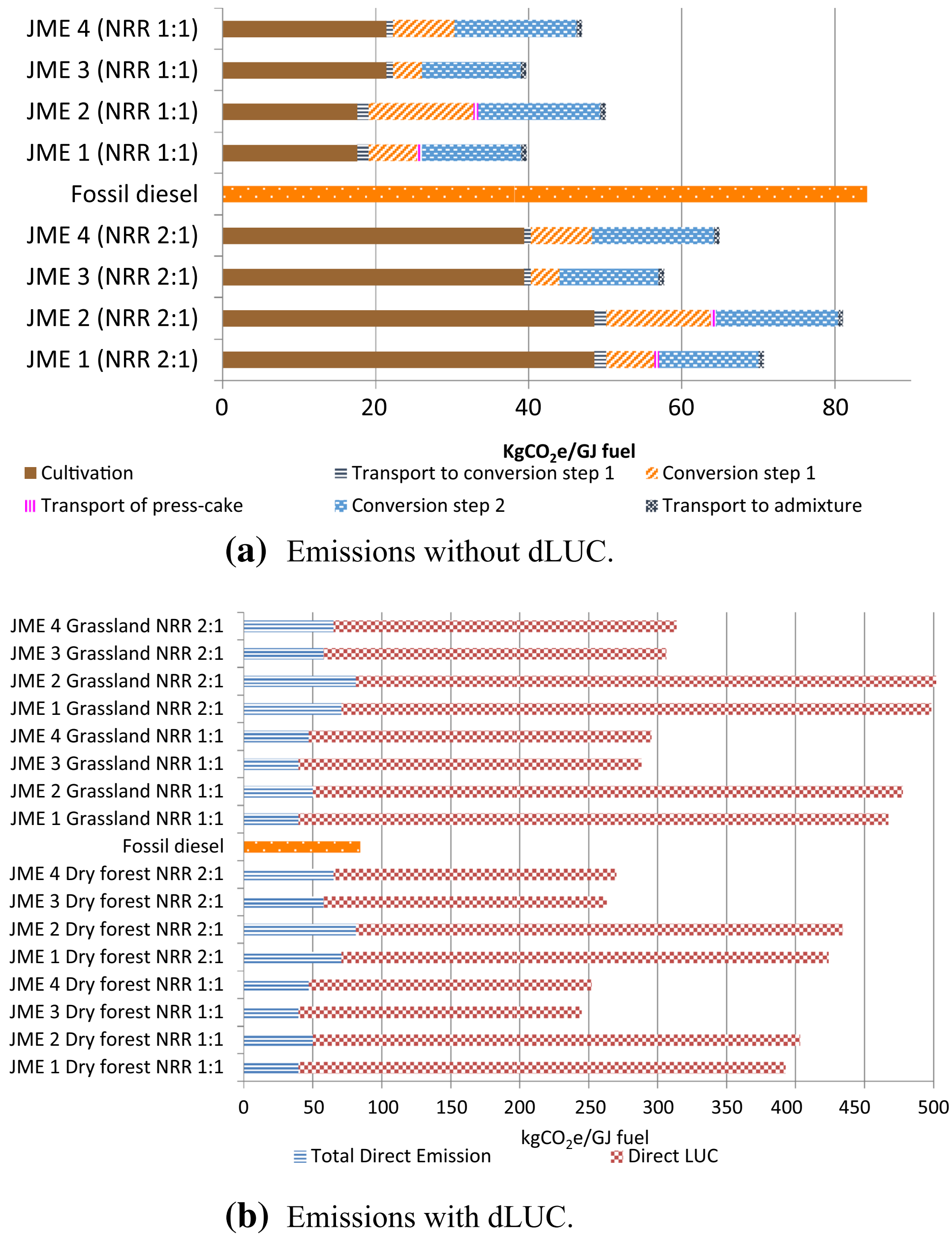

Fig. 3 Comparison between the different systems: **a** Emissions without dLUC with ratios of NRR 1:1 and NRR 2:1. **b** Emissions of the evaluated systems including dLUC with NRR 1:1 and NRR 2:1

Ratios emissions with and without dLUC

The impact of dLUC is so significant that it generates negative mitigation in all the systems. If dLUC occurs, GHG emissions of JME are always higher than the fossil diesel, and can reach up to 504 kg CO_2e/GJ_{fuel} (Fig. 3), when Jc is planted on grasslands. This value is more than six times higher than the fossil reference.

Energy balance

In Fig. 4 we show the results of the energy balance, expressed as the ratio of fossil to renewable energy. In Table 6 we show the partial FE:RE and EROI values for each phase of biofuel production and final values, once production is completed. The EROI shows values greater than 1 for every system, ranging from 1.6 to 2.2, since they consume less fossil fuel energy than that provided by biodiesel. The system, which showed the most favorable energetic relationship, was JME3 with 2.2 $GJ_{biodiesel}/GJ_{fossil}$, followed by JME1 with 1.9 $GJ_{biodiesel}/GJ_{fossil}$.

For all systems the greatest consumption of fossil energy occurs in the industrial phase due to the use of electricity, heat energy and reagents (methanol and sodium hydroxide), represented from 67% (0.31 $GJ_{fossil}/GJ_{biodiesel}$) up to 75% (0.5 $GJ_{fossil}/GJ_{biodiesel}$) in JME3

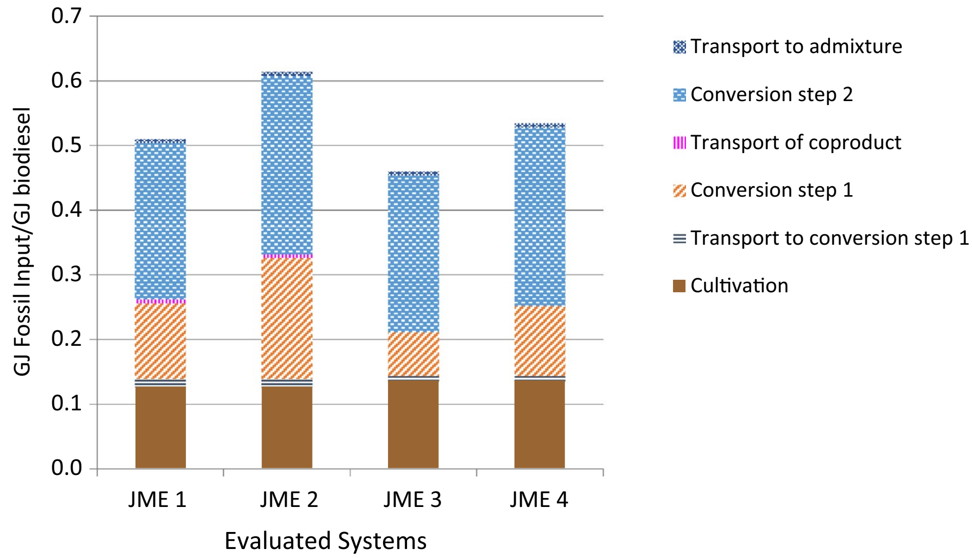

Fig. 4 Ratios FE:RE for four production systems

Table 6 Energetic relationships for each phase of processing

	JME 1 $GJ_{Fossil\ input}/GJ_{biodiesel}$	JME 2 $GJ_{Fossil\ input}/GJ_{biodiesel}$	JME 3 $GJ_{Fossil\ input}/GJ_{biodiesel}$	JME 4 $GJ_{Fossil\ input}/GJ_{biodiesel}$
Production of biomass	0.126	0.126	0.136	0.136
Transport of biomass	0.013	0.013	0.008	0.008
Conversion step I	0.117	0.187	0.068	0.109
Transport of coproduct	0.005	0.005	–	–
Conversion step II	0.242	0.276	0.242	0.276
Transport to fuel storage for admixture	0.006	0.006	0.006	0.006
FE:RE $_{Gfossil\ input/GJbiodiesel}$	0.509	0.614	0.459	0.534
EROI $GJ_{biodiesel}/GJ_{fossil\ input}$	1.96	1.63	2.18	1.87

and JME2, respectively. Both JME1 and JME3 showed a greater contribution by electricity and reagents, while JME2 and JME4 showed higher values resulting from the use of electricity and heat energy. The alternative of using fruit husks as combustible material reduces consumption of fossil energy in this phase (from 0.5 $GJ_{fossil}/GJ_{biodiesel}$ to 0.4 $GJ_{fossil}/GJ_{biodiesel}$). The agricultural phase presents the second highest consumption of fossil fuel with values near 0.1 $GJ_{fossil}/GJ_{biodiesel}$, 21% and 30% of the total energy consumption in JME2 and JME3, respectively. JME1 and JME2 showed that pesticides were the greatest contributor to emissions, while JME3 and JME4 showed that the greatest contributions resulted from chemical fertilizer use. The fruit transport phase, transport to refinery terminals and transport of the residual press-cake byproduct for the two systems, including it, result in marginal values, which do not go above 3% of the total emissions.

Sensitivity analysis for yields

In cases where dLUC generates high emissions, a sensitivity analysis was conducted regarding the variation in yields: LCA was done for each yield (results are shown in Fig. 5). The full offset of emissions was only achieved when productivity was greater than 4.8 t_{seed}/ha in JME3 and above 12 t_{seed}/ha for JME2. Currently, there is no place or plot, which yields above 1.7 t_{seed}/ha in Mexico.

Conclusions and recommendations

Our major findings are: first, energy balance was positive in the four systems evaluated; second, when *JME* was produced with land-use change, none of the systems evaluated reduced GHG emissions; third, the full offset of emissions

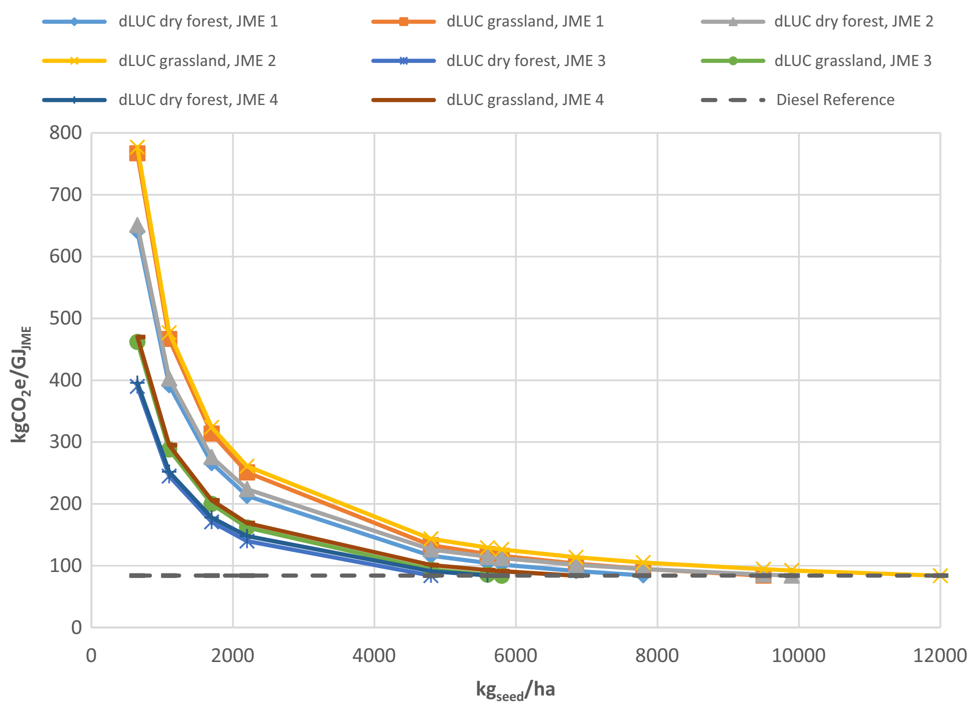

Fig. 5 Relationship of emissions for evaluated systems for different yields

was only achieved with yields higher than 4.8 t_{seed}/ha in JME3 (on tropical dry forest) and above 12 t_{seed}/ha for JME2 (on grassland).

In order to obtain both, a better energetic relationship and better mitigation of GHG, we recommend: (1) the use of fruit husks as a fuel and a source of electricity production in the industrial phase (cogeneration with biomass in the processing plant); (2) more efficient use of chemical fertilizers; (3) seeking alternative fertilizers (with a higher sustainability factor).

The emissions related to dLUC make up the greatest percentage of total emissions. Our recommendation here would be to use degraded land areas, where carbon density is lower than that of the *J. curcas* crop; however, in this type of land there are no reliable data indicating that *J. curcas* yields would be high enough to compensate for the investment.

The sources of emissions that have the greatest impact on total emission values are strongly related to nitrogenous fertilizer production and resulting volatilization of N_2O. An adequate use of chemical fertilizer, apart from the application of other nutrient sources (like organic fertilizer), may help reduce total emissions if adequately managed and applied. Although *J. curcas* is native to Mexico, there is still very little technical-agricultural knowledge of the *J. curcas* crop, so that production of JME occurs without estimations of seed yields and fertilizer use or specific procedural guidelines. Therefore, more research is necessary to generate more reliable and accurate data about the *J. curcas* crop. Given the results we obtained through this methodology, we strongly recommended further studies to be carried out in Mexico before developing additional projects related to JME production.

We would like to emphasize that the methodology proposed here could be used in any country to assess the greenhouse gas emissions and fossil fuel energy use for other feedstocks and products derived from biomass. This study results can also serve as a reference for other studies that evaluate specific aspects of liquid biofuels' sustainability.

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