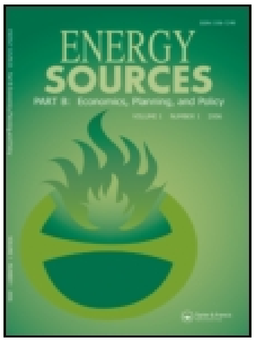

Energy Sources, Part B: Economics, Planning, and Policy

ISSN: 1556-7249 (Print) 1556-7257 (Online) Journal homepage: https://www.tandfonline.com/loi/uesb20

Evaluation of life-cycle assessment of *Jatropha* biodiesel

Raphael Muzondiwa Jingura & Reckson Kamusoko

To cite this article: Raphael Muzondiwa Jingura & Reckson Kamusoko (2016) Evaluation of life-cycle assessment of *Jatropha* biodiesel, Energy Sources, Part B: Economics, Planning, and Policy, 11:5, 396-403, DOI: 10.1080/15567249.2011.637546

To link to this article: https://doi.org/10.1080/15567249.2011.637546

Published online: 13 Jun 2016.

ENERGY SOURCES, PART B: ECONOMICS, PLANNING, AND POLICY
2016, VOL. 11, NO. 5, 396–403
http://dx.doi.org/10.1080/15567249.2011.637546

Evaluation of life-cycle assessment of *Jatropha* biodiesel

Raphael Muzondiwa Jingura and Reckson Kamusoko

Directorate of Research and Postgraduate Studies, Chinhoyi University of Technology, Chinhoyi, Zimbabwe

ABSTRACT
This paper provides an analysis of life-cycle assessment (LCA) of Jatropha biodiesel with a view to outline the environmental quality norms of Jatropha biodiesel. The underlying issue is that biofuels need to mitigate the effects of climate change and provide sustainable energy alternatives to fossil fuels. Thus, there is need for empirical evidence on the sustainability of Jatropha biodiesel in order to inform both biofuels policies and development of options for technical intervention to improve the environmental footprint of Jatropha biodiesel. Ten LCAs of Jatropha biodiesel are analyzed in this paper. The paper considers impact categories, which include energy and greenhouse gas (GHG) balance, land-use impact, acidification, and eutrophication. The general trend emerging from this analysis is that although Jatropha biodiesel has positive energy and GHG balances, there are site-specific variances and numerous opportunities for improvement.

KEYWORDS
Biodiesel; energy balance; greenhouse gas balance; *Jatropha*; life-cycle assessment

Introduction

Liquid biofuels for transportation continue to receive increasing attention worldwide. Biodiesel is among the fastest-growing liquid biofuels on the market today. It is mainly produced from seed oil of plants such as *Jatropha*, soya bean, and oil palm. *Jatropha* has been promoted extensively as an energy crop for the production of biodiesel in the tropics. It has been marketed as a high-yielding oil crop, which is drought tolerant and has low nutrient, water, and management requirements and is well adapted to grow on wasteland unsuitable for food production (Achten et al., 2010).

Jatropha is a major energy crop in the South and is central to sustainable biofuel programs in many countries. In 2008 *Jatropha* plantations occupied 936,000 ha globally (Achten et al., 2010). Growth in *Jatropha* production is estimated to reach 12,800,000 ha by 2015 (GEXSI, 2008). The drivers for liquid biofuels are reduction of dependency on fossil fuels and climate change mitigation (Tomomatsu and Brent, 2007). There is debate over the environmental sustainability norms of biofuels. The sustainability profile of biofuels has been questioned by several researchers (Searchinger et al., 2008; Fargione et al., 2008). The issues of concern include direct and indirect land-use impacts, decline of carbon stocks, water depletion and pollution, biodiversity loss, and air-quality degradation (Menichetti and Otto, 2009; Cherubini and Strømman, 2011).

Life-cycle assessment (LCA) is used to determine the environmental impact of biofuels (Kaltschmitt et al., 1997; Achten et al., 2007). The LCA approach evaluates the environmental flows related to a product or a service during all life-cycle stages (Menichetti and Otto, 2009). It is regulated by the International Organisation for Standardisation (ISO) 14040:2006 and 14044:2006 standards. According to the ISO 14044:2006 (ISO, 2006) an LCA study is divided into four separate but interacting phases. These are scoping, inventory analysis, impact assessment, and interpretation.

CONTACT Raphael Muzondiwa Jingura rjingura@cut.ac.zw Directorate of Quality Assurance, Chinhoyi University of Technology, P.Bag 7724, Chinhoyi, Zimbabwe.

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uesb.

Until recently, data on LCA of *Jatropha* biodiesel has been scarce. However, there are now a number of studies based on the LCA methodology that have been published for *Jatropha* biodiesel (Reinhardt et al., 2007; Prueksakorn and Gheewala, 2008; Ndong et al., 2009; Xunmin et al., 2009; Achten et al., 2010). This paper seeks to evaluate the LCA of *Jatropha* biodiesel with a view to outline current knowledge under different value chain conditions and make an inference on the case of *Jatropha* biodiesel in sustainable biofuel production systems.

Generic LCA of *Jatropha* biodiesel

A generic LCA for *Jatropha* biodiesel, which is site-independent, is used here to illustrate the fundamental components in the production and use of *Jatropha* biodiesel on a well-to-wheel basis. There are basically four major components of the *Jatropha* biodiesel system. These are: (i) feedstock production (cultivation); (ii) oil extraction; (iii) conversion of seed oil into biodiesel (transesterification); and (iv) use of biodiesel (engine combustion). System boundaries of the *Jatropha* biodiesel are shown in Figure 1. Table 1 summarizes the flow processes, inputs, and outputs associated with each stage in the *Jatropha* biodiesel system.

The most relevant impact categories are energy balance, global warming potential (GWP), and land-use impact (Achten et al., 2007). The different impact categories in LCA systems are shown in Table 2. Net energy gain (NEG) is one of the accepted indices for analyzing the energy efficiency of biofuels (Nguyen et al., 2007). The net energy ratio (NER) measures the efficiencies of bioenergy processes. Greenhouse gas (GHG) emissions are used to estimate the GWP of biofuels. Land-use impact focuses on the impact of the new use of land for production of energy crops against a reference system such as natural vegetation of the land. Land-use impact considers ecosystem structural quality (ESQ) and ecosystem functional quality (EFQ) (Achten et al., 2007, 2010).

Analysis of LCAs of *Jatropha* biodiesel

This paper analyses results from 10 LCA studies of *Jatropha* biodiesel across different locations and scope. Some information on these studies is shown in Table 3. Data in Table 3 highlight two main issues about LCA of *Jatropha* biodiesel. First, that data on LCA studies for *Jatropha* biodiesel have emerged very recently and are still limited, and second that the geographical spread of the studies is

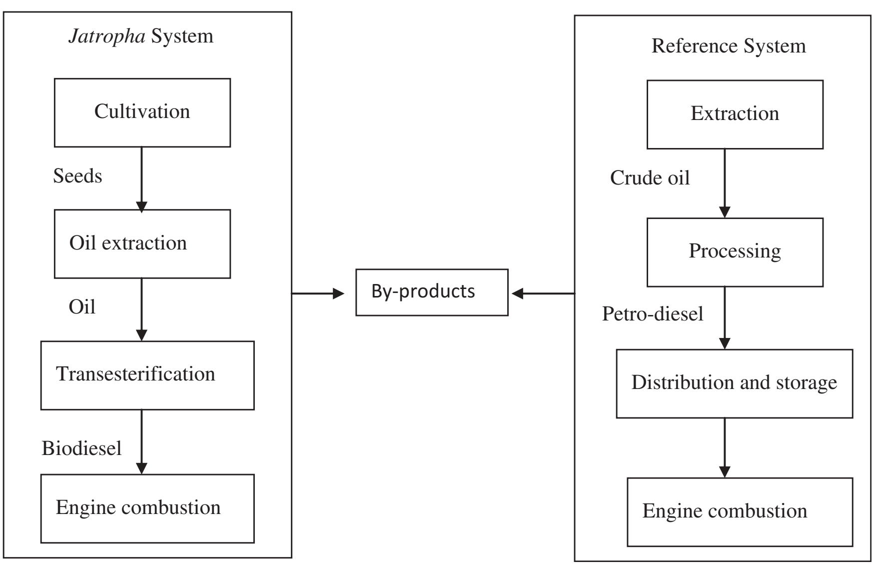

Figure 1. System boundaries of the *Jatropha* system (adapted from Achten, 2010).

Table 1. Flow processes, inputs, and outputs of the *Jatropha* biodiesel system.

Phase	Processes	Inputs	Products	By-products
(a) Cultivation				
Seedling production	– Seeding in nurseries	– Energy, machines, infrastructure	– Air emissions	-
Plantation establishment	– Planting cuttings – Transplantation – Direct seeding – Land preparation	– Energy, machines, auxiliaries	– Air emissions – Standing biomass – Seeds	–
Plant management	– Pruning, canopy management, fertilising, irrigation, harvesting	– Energy, machines, infrastructure auxiliaries	– Air emissions	– Woody cuttings
(a) *Oil extraction*	– Mechanical – Solvent-based	– Energy, machines, infrastructure, auxiliaries	– Air emissions – Raw oil – Wastewater	– Seed cake – Fruit shells – Glycerol
(a) *Transesterification*	– Catalysis – Transport of biodiesel	– Energy, infrastructure	– Air emission – Biodiesel – Wastewater	
(a) *Use*	– Combustion	–	– Air emissions	–

Table 2. Types of impact categories in LCA of bioenergy systems.

Impact category	Responsible full chain processes	Components
Energy balance	– Cultivation, transportation, processing, distribution	– Total life-cycle energy input and output
Greenhouse gas balance	– Feedstock production – End-use of biodiesel	– CO_2 – CH_4 – N_2O
Airbone emissions	– Feedstock production – End-use of biodiesel	– SO_x – PM – NO_x
Eutrophication and acidification	– Fertilizing	– NH_3 – NO_3
Land use	– New land-use	– ecosystem structure – ecosystem functioning

Table 3. Geographical spread of LCA studies of *Jatropha* biodiesel.

Authors	Year	Country of study
Prueksakorn and Gheewala	2006	Thailand
Prueksakorn and Gheewala	2008	Thailand
Achten	2010	India
Reinhardt et al.	2007	India
Xunmin et al.	2009	China
Gmünder et al.	2009	India
Ndong et al.	2009	Ivory Coast
Whitaker and Heath	2008	India
Lam et al.	2009	Malaysia
Sampattagul et al.	2007	Thailand

still very limited. Nine of the studies are in Asia and only one from Africa. However, these early data are useful as they provide emerging trends on the LCA of *Jatropha* biodiesel and are a base for judicious extrapolation to other *Jatropha* biodiesel systems.

Energy balance

The studies report energy benefits for *Jatropha* biodiesel. Values for NEG range from 189 kJ FU^{-1} (Achten et al., 2010) to 1222–8051 GJ ha^{-1} for 20 years for different scenarios (Prueksakorn and Gheewala, 2008). The NER values are 1.85 (Achten et al., 2010), 1.92 (Lam et al., 2009), 1.9 (Whitaker and Heath, 2008), 2.0 (Xunmin et al., 2009), 1.93–11.99 for worst and best case scenarios (Preuksakorn and Gheewala, 2008) and 4.7 (Ndong et al., 2009). Best case refers to more intensive cultivation of *Jatropha*. These results show a similarity in NER values across the studies with the exception of Preuksakorn and Gheewala (2008). NER is a problematic metric (Whitaker and Heath, 2008). It is difficult to compare NER between studies as it is often poorly defined and strongly influenced by the analyst's method of calculation (Whitaker and Heath, 2008).

The NER values are all above 1, meaning that *Jatropha* biodiesel has positive energy balance. What is clear is that there is a wide range of cultivation practices for *Jatropha* and this influences energy balance. It is also important to note that differences in NER values also arise due to differences in the selection of by-products, which are considered as energy outputs. For example, Achten et al. (2010) only considered glycerine as a by-product, whereas Prueksakorn and Gheewala (2008) considered the whole gamut from husks, seed cake to wood.

An important dimension to consider in energy balance analysis is the decomposition of energy consumption pathway. The pathway comprises two main stages: feedstock production and fuel production (Table 1). At the feedstock production stage, energy consumption drivers are land preparation, irrigation, fertilizer use, and secondary agronomic practices. At the fuel stage energy consumption is due to seed cracking, oil extraction, filtration, and transesterification. Considering proportions rather than absolute values, decomposition of energy consumption in four different studies is shown in Figure 2.

The decomposition of energy shown in Figure 2 clearly shows that most of the energy consumption is at the biodiesel production and use stages. At the feedstock production stage the main contributors to energy consumption are fertilizers and irrigation. Examples of values for fertilizer use and irrigation as proportions of total energy consumption are 30% and 13%, respectively (Preuksakorn and Gheewala, 2008). Where *Jatropha* is produced in a low-input system and under rain-fed conditions, energy consumption at the feedstock stage is minimal, for example, 12% (Ndong et al., 2009; Achten, 2010). For sustainable production, use of bio-fertilizers is more beneficial to the full chain system of *Jatropha* biodiesel. Preuksakorn and Gheewala (2008) reported an energy consumption level of 260 GJ for production of inorganic fertilizer, which can be substantially

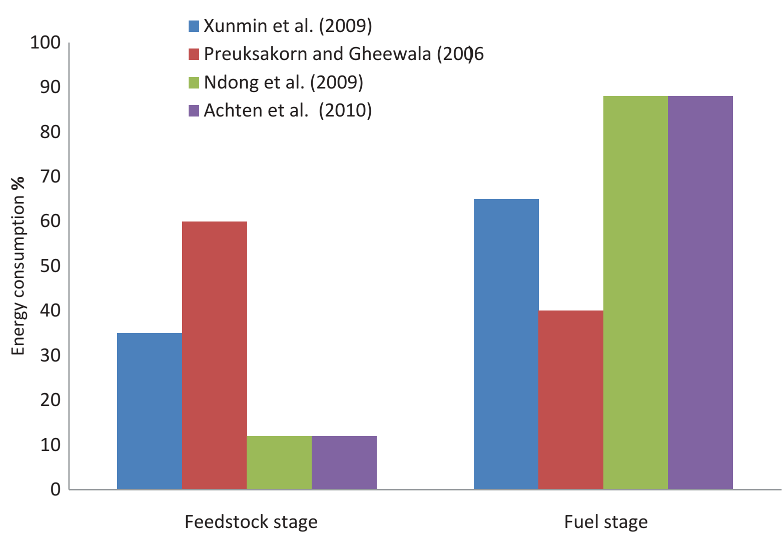

Figure 2. Energy consumption in feedstock and fuel production stages of *Jatropha* biodiesel.

reduced by use of bio-fertilizers. *Jatropha* seed cake (a by-product of oil extraction) is an excellent bio-fertilizer with more nutrients than chicken and cattle manure. A kilogram of *Jatropha* seed cake is equivalent to 0.15 kg of N:P:K (40:20:10) chemical fertilizer (Openshaw, 2000). Furthermore, conservation agriculture practices would lower the energy cost of fertilizers, but there might be a trade-off with seed yield (Von Maltitz and Brent, 2008).

At the fuel stage the main energy consumer is the transesterification process. As a proportion of whole life-cycle energy consumption, transesterification accounts for 65% (Xunmin et al., 2009) and 61% (Ndong et al., 2009) of the total energy consumption. In the transesterification process, the production and use of methanol is the biggest energy consumer (Achten et al., 2010). Other processes such as seed cracking, oil refining, and transportation do not consume much energy as compared to the transesterification process. Most of the energy consumed at these stages is produced with fossil fuels. Fossil-input energy ratio, which is not given in most of these studies, would be a good measure of sustainability.

It is worth noting that transesterification, as stated above, is a big energy-consuming process and its negative impact on the energy balance can be marginalized (Basili and Fontini, 2010). One alternative is that the base-catalyzed transesterification process could be by-passed and pure vegetable oil used (Basili and Fontini, 2010). This is because there is technology that can use pure vegetable oil. For example, the Elsbett-Engine is designed to use pure vegetable oil. However, the bottom line still remains that even with transesterified oil, the net energy balance is positive almost everywhere (Preuksakorn and Gheewala, 2006).

GHG balance

It is worth re-stating that mitigation of climate change is one of the major reasons for the development and deployment of biofuels. Thus, a GWP index for *Jatropha* biodiesel is a useful metric for this purpose.

There is consensus in the studies analyzed in this paper that *Jatropha* biodiesel has emission savings compared to fossil fuels. Savings rates reported range from 49% (Xunmin et al., 2009) to 85% (Gmünder et al., 2009). Data on GHG emissions of *Jatropha* biodiesel are shown in Table 4. However, Sampattagul et al. (2007) reported that the environmental impacts of *Jatropha* biodiesel are higher than fossil diesel.

GHG balance is also a problematic metric. The purpose of the data in Table 4 is not to compare the outcomes of the different studies but to show the general trend across the studies. This is because there is a wide variation on the methodology to estimate GHG emissions, mainly due to the selection of system boundaries, allocation of procedures, inclusion of land-use change impacts, and others (Cherubini and Strømman, 2011). In addition, LCA studies use different functional units.

One fundamental issue on GHG balance is to understand the decomposition of the emissions into various cause categories. It would appear from Table 4 that the cause–effect balance between feedstock and biodiesel production and use is not a static relationship but varies from system to system. Considering the feedstock production side, the main driver of GHG emissions is fertilizer production and use. Contributions of fertilizers to GHG emissions at the feedstock production phase vary from 30% (Preuksakorn and Gheewala, 2006), to 37% (Xunmin et al., 2009), 93% (Ndong et al., 2009), and 99% (Achten et al., 2010). Nitrogen fertilizer is the most important contributor of GHG due to N_2O emissions (Reinhardt et al., 2007; Achten, 2010). GWP of N_2O is 320 times that of CO_2 (Zah et al., 2007). Crutzen et al. (2008) showed that the yield of N_2O can be in the range of 3–5%, which is three to five times larger than assumed in most LCAs. This has serious implications on climate and is an issue for consideration.

When grown under irrigation, substantial amounts of GHG are also produced due to supply of power to pump water. Preuksakorn and Gheewala (2006) ascribed 26% and Whitaker and Heath (2008) 28% of GHG produced during the feedstock production phase to irrigation. Secondary practices such as pesticide and herbicide application can contribute more than 2% of GHG emitted during the cultivation of *Jatropha* (Ndong et al., 2009).

Table 4. Greenhouse gas emissions of the *Jatropha* biodiesel system.

Reference	Total savings (%)	Emission FU^{-1} (gCO_2 eq.)	Emission contribution (%)	
			Feedstock production	Fuel production and use
Ndong et al. (2009)	72	23.5	52	48
Prueksarkon and Gheewala (2006)	77	56.7	10	90
Gmünder et al. (2009)	85	74.6	21	79
Xunmin et al. (2009)	49	52.0	47	53
Achten et al. (2010)	55	123.7	86	14
Whitaker and Heath (2008)	62	5.1[a]	44	56
Sampattagul et al. (2007)	–	–	45	55

FU = production and combustion of 1 MJ *Jatropha* biodiesel.
[a]gCO_2 eq. per gross-tonne kilometres.

At the fuel production and use stages, transesterification accounted for 11% (Achten et al., 2010), 17% (Ndong et al., 2009), and 27% (Xunmin et al., 2009) of total GWP of *Jatropha* biodiesel. Most of this is due to methanol production. Final combustion of *Jatropha* biodiesel produces GHG, but these are basically referred to as biogenic and GHG-neutral as they are of biomass origin and thus absorbed from the atmosphere by *Jatropha* plants during growth (Preuksakorn and Gheewala, 2006). Data from a *Jatropha* project in Egypt show that 1600 plants per hectare produce about 80 t per year of biomass with storage of 5.5–20 t of carbon per year (Basili and Fontini, 2010). What is also worth noting from these studies is that the most energy-demanding processes are not necessarily the ones that emit the most GHG.

Land-use impact

Production of *Jatropha* is a land-intensive practice with both negative and positive impacts on land use. It is important to identify the various options that can be used to convert existing land into *Jatropha* plantations in order to consider the likely impacts of such approaches. The baseline is that all land that is available always has specific roles it is playing in the socio-ecosystem and its conversion to *Jatropha* production will have various impacts.

It is important to outline the options for cultivation of *Jatropha*. The different case scenarios provide a basis for proper evaluation of land-use impact of *Jatropha* biodiesel. *Jatropha* cultivation can be carried out through conversion of the following lands: (1) existing cropland; (2) abandoned agricultural land; (3) natural vegetation; (4) degraded natural vegetation; and (5) wasteland (Von Maltitz and Brent, 2008). This will vary the land-use impact of *Jatropha* biodiesel. Land-use impact of *Jatropha* biodiesel reported in the studies under review includes the following:

(a) Changing wastelands into *Jatropha* plantations triggers an improvement of the ESQ but a reduction in EFQ. The improvement in ESQ means that the *Jatropha* plantations have higher storage capacity in terms of biomass, structure, and biodiversity than wasteland. Decrease in EFQ means that *Jatropha* plantations have less control over water, material, and nutrient fluxes than wasteland (Achten et al., 2010).
(b) Considering a 'no vegetation' or 'scarce vegetation' situation *Jatropha* cultivation leads to advantages in carbon balance. *Jatropha* achieves an average CO_2 stock of 32.9 t in its biomass per hectare during consecutive rotations (Reinhardt et al., 2007).

There is limited empirical data in the literature on the land-use impact of *Jatropha* biodiesel. What would seem to be the case is that the impact will depend on variables such as site quality, nature of land use, and crop management (Basili and Fontini, 2010). *Jatropha* is basically presented as a crop that is suitable for cultivation on wastelands, more so given the conflict between production of energy and food crops. In such cases, *Jatropha* is more inclined to have more positive impacts on land use. GEXSI (2008) reported that *Jatropha* production has not led to destruction of primary forests as most of the land used is marginal land.

Other environmental impacts

Three studies (Sampattagul et al., 2007; Gmünder et al., 2009; Achten et al., 2010) provide some information on other environmental impacts of *Jatropha* biodiesel such as acidification and eutrophication. Achten et al. (2010) reported a 49% increase in acidification potential compared to the reference system. These are associated with NH_3 emissions at the cultivation stage and final combustion of biodiesel.

Jatropha biodiesel has a higher eutrophication potential than fossil diesel (Gmünder et al., 2009; Achten et al., 2010). This is mainly caused by phosphate, phosphorus, and nitrate leaching to surface and groundwater (Gmünder et al., 2009). Sampattagul et al. (2007) showed that most of the acidification is due to biodiesel utilization and agronomy accounts for most of the eco-toxicity.

Bioenergy and water nexus

It is worth noting that little attention has been paid to water as a limiting factor in *Jatropha* production. As such, freshwater use has not been considered in LCA. However, water is now being considered in LCA studies (Gheewala et al., 2011; Otto et al., 2011). Bioenergy and water are linked and there might be trade-offs to manage between climate change mitigation and water in bioenergy systems (Gheewala et al., 2011). It is important for LCA of *Jatropha* biodiesel to be fully complemented with the associated water footprint of *Jatropha*.

Conclusion

The massive investment in *Jatropha* plantations, which are expected to cover 12,800,000 ha worldwide by 2015, requires to be informed by sufficient knowledge on the life-cycle impacts of the plant. That *Jatropha* biodiesel is a suitable alternative to petro-diesel in terms of mitigation of climate change needs to be supported by life-cycle data. There is little doubt on the environmental benefits of *Jatropha* biodiesel when compared to petro-diesel. However, there is need for more work to be done to complement the studies reported in this paper.

Although *Jatropha* is described as a crop suitable for cultivation on wastelands with low inputs, it is very difficult to establish an industry that requires a large and reliable supply of feedstock based on low-input agriculture. Thus, use of inputs such as fertilizers, irrigation, and pesticides will be unavoidable in commercial *Jatropha* production. In addition, transesterification will remain the major conversion technology. These are the major contributors to GHG emissions and energy consumption. From a sustainable development perspective, the studies considered here are only indicative and point out intervention opportunities to improve life-cycle performance of *Jatropha* biodiesel. These are:

- Optimization of inputs and judicious use of bio-fertilizers at the cultivation stage
- Minimization and/or low-energy consuming irrigation
- Optimization of transesterification processes
- Need to consider water footprint of *Jatropha*

References

Achten, W. M. J., Almeida, J., Fobelets, V., Bolle, E., Mathijs, E., Singh, V. P., Tiwari, D. N., and Muys, B. 2010. Life cycle assessment of *Jatropha* biodiesel as transportation fuel in rural India. *Appl. Energy* 87:3652–3660.

Achten, W. M. J., Mathijs, E., Verchot, L., Singh, V., Singh, P., Aerts, R., and Muys, B., 2007. *Jatropha* biodiesel fuelling sustainability? *Biofuels. Bioprod. Biorefin.* 1:283–291.

Basili, M., and Fontini, F. 2010. *Biofuel from* Jatropha curcas*: Environmental Sustainability and Option Value*. Available at: http://www.unisi.it/d12/20100519144204853.biofuel.pdf (accessed on September 15, 2011).

Cherubini, F., and Strømman, A. H. 2011. Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresour. Technol.* 102:437–451.

Crutzen, P. J., Mosier, A. R., Smith, K. A., and Winiwarter, W. 2008. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys.* 8:389–395.

Fargione, J., Hill, J., Tilman, D., Polasky, S., and Hawthorne, P. 2008. Land clearing and the biofuel carbon debt. *Science* 319:1235–1238.

GEXSI. 2008. *Global Market Study on* Jatropha *– Final Report*. Berlin, Germany: GEXSI LLP. Available at: http://tinyurl.com/cnyn44 (accessed on September 6, 2011).

Gheewala, S. H., Berndes, G., and Jewit, G. 2011. The bioenergy and water nexus. *Biofuels. Bioprod. Biorefin.* 5:353–360.

Gmünder, S. M., Zah R., Bhatacharjee, S., Classen, M., Mukherjee, P., and Widmer, R. 2009. Life cycle assessment of village electrification based on straight *Jatropha* Oil in Chhattisgarh, India. *Biomass Bioenergy* 34:347–355.

International Organization for Standardization. 2006. *Environmental Management – Life Cycle Assessment – Principles and Framework*. Geneva, Switzerland: ISO 14040.

Kalitschmitt, M., Reinhardt, G. A., and Stelzer, T. 1997. Life cycle analysis of biofuels under different environmental aspects. *Biomass Bioenergy* 12:121–134.

Lam, M. K., Lee, K. T., and Mohamed, A. R. 2009. Life cycle assessment for the production of biodiesel: A case study in Malaysia for palm oil versus *Jatropha* oil. *Biofuels. Bioprod. Biorefin*. 3:601–612.

Menichetti, E., and Otto, M. 2009. Energy balance and greenhouse gas emissions of biofuels from a life cycle perspective. In: *Biofuels: Environmental Consequences and Interactions with Changing Land Use*. Howarth, R. W., Bringezu, S. (Eds.). Ithaca, NY: Cornell University. pp. 81–109.

Ndong, R., Montrejaud-Vignoles, M., Girons, O. S., Gabrielle, B., Pirot, R., Domergue, M., and Sablayrolles, C. 2009. Life cycle assessment of biofuels from *Jatropha curcas* in West Africa: A field study. *Global Biol. Bioenergy* 1:197–210.

Nguyen, T. L. T., Gheewala, S. H., and Garivait, S. 2007. Full chain energy analysis of fuel ethanol from cassava in Thailand. *Environ. Sci. Technol.* 41:4135–4142.

Openshaw, K. 2000. A review of *Jatropha curcas*: an oil plant of un-fulfilled promise. *Biomass Bioenergy* 19:1–15.

Otto, M., Berndes, G., and Fritsche, U. 2011. The bioenergy and water nexus. *Biofuels. Bioprod. Biorefin.* 5:343–346.

Preuksakorn, K., and Gheewala, S. H. 2008. Full chain energy analysis of biodiesel from *Jatropha curcas* L. in Thailand. *Environ. Sci. Technol.* 42:3388–3393.

Preuksakorn, K., and Gheewala, S. H. 2006. Energy and greenhouse gas implications of biodiesel production from *Jatropha curcas* L. *The 2nd Joint International Conference on Sustainable Energy and Environment (SEE 2006)*, Bangkok, Thailand, November 21–23.

Reinhardt, G., Gärtner, S., Rettenmaier, N., Münch, J., and Falkenstein, E. 2007. *Screening life cycle assessment of Jatropha biodiesel*. Final Report, Heidelberg: Institute for Energy and Environmental Research, 56 pp.

Sampattagul, S., Suttibut, C., and Yucho, S. 2007. Life cycle management of *Jatropha* biodiesel production in Thailand. *3rd International Conference on Life Cycle Management Zurich*, University of Zurich at Irchel, August 27–29. Available at: http://www.lcm2007.org.paper/326.pdf (accessed on September 27, 2011).

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., and Heyes, D. Y. T. H. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. *Science* 319:1238–1240.

Tomomatsu, Y., and Brent, S. 2007. *Jatropha curcas* biodiesel production in Africa: Economics and potential value chain development for smallholder farmers. WP54. Nairobi: World Agroforestry Centre, 33p.

Von Maltitz, G. P., and Brent, A. 2008. *Assessing the Biofuel Options for Southern Africa*. Available at: http://www.researchspace.csir.co.za/dspace/bitstream/10204/2579/1/Von%20Maltitz_2008.pdf (accessed on January 20, 2011).

Xunmin, O., Xiliang, Z., Shiyan, C., and Qingfang, G. 2009. Energy consumption and GHG emissions of six biofuels pathways by LCA in (the) People's Republic of China. *Appl. Energy* 86:S197–S208.

Whitaker, M., and Heath, G. 2008. *Life cycle assessment of the use of* Jatropha *biodiesel in Indian Locomotives*. Technical Report NREL/TP-6A2-44428, Colorado, USA: National Renewable Energy Laboratory.

Zah, R., Böni, H., Gauch, M., Hischier, R., Lehman, M., and Wäger, P. 2007. *Life Cycle Assessment of Biofuels*. Bern, Switzerland: EMPA. Available at: http://www.empa.ch/biofuels (accessed on September 20, 2011).