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Title

Life cycle assessment of *Jatropha* biodiesel as transportation fuel in rural India

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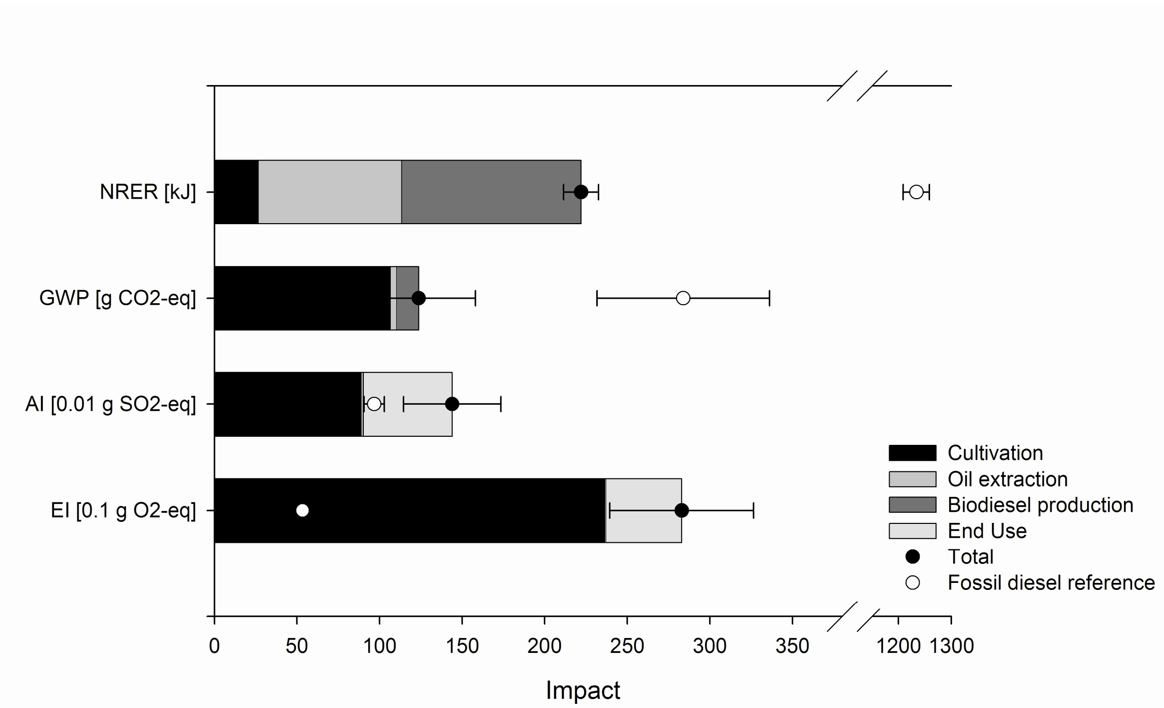
Abstract

Since 2003 India has been actively promoting the cultivation of *Jatropha* on unproductive and degraded lands (wastelands) for the production of biodiesel suitable as transportation fuel. In this paper the life cycle energy balance, global warming potential, acidification potential, eutrophication potential and land use impact on ecosystem quality is evaluated for a small scale, low-input *Jatropha* biodiesel system established on wasteland in rural India. In addition to the life cycle assessment of the case at hand, the environmental performance of the same system expanded with a biogas installation digesting seed cake was quantified. The environmental impacts were compared to the life cycle impacts of a fossil fuel reference system delivering the same amount of products and functions as the *Jatropha* biodiesel system under research. The results show that the production and use of *Jatropha* biodiesel triggers an 82% decrease in non-renewable energy requirement (Net Energy Ratio, NER=1.85) and a 55% reduction in global warming potential (GWP) compared to the reference fossil-fuel based system. However, there is an increase in acidification (49%) and eutrophication (430%) from the *Jatropha* system relative to the reference case. Although adding biogas production to the system boosts the energy efficiency of the system (NER=3.40), the GWP reduction would not increase (51%) due to additional CH_4 emissions. For the land use impact, *Jatropha* improved the structural ecosystem quality when planted on wasteland, but reduced the functional ecosystem quality. Fertilizer application (mainly N) is an important contributor to most negative impact categories. Optimizing fertilization, agronomic practices and genetics are the major system improvement options.

Graphical abstract

Besides other environmental impacts of *Jatropha* biodiesel this study shows an 82% reduction in energy requirement and a 55% reduction in global warming potential compared to the reference system.



(pictogram is uploaded as “Graphical abstract.TIFF”)

Keywords

biogas, energy balance; greenhouse gas balance; impact assessment; *Jatropha curcas*; land use

1. Introduction

In 2009 the Government of India approved the National Policy on Biofuels aiming at a 20% blend of biofuels with gasoline and diesel by 2017 [1]. In 2007, India consumed about 38 million tonnes of petroleum products in the transport sector [2] and is expected to double this consumption by 2030 [3]. In 2005, 71% of the transportation fuel was diesel [3]. Hence, the blending target implies a large increase in biodiesel production for which India has set high hopes on *Jatropha curcas* [3-5]. India intends to introduce *Jatropha* in wastelands and degraded lands only, to avoid conflict with food production and to simultaneously reclaim these unproductive areas, enhance rural socio-economic development and produce fuel [6,7]. It is estimated that India holds 40-64 million ha of wasteland area, which could be partially or fully cultivated with *Jatropha* [3,6]. Following the yield estimation of Francis et al [6] this area could yield 19.4-31.1 million t *Jatropha* biodiesel. By the end of 2007, the Ministry of Rural Development estimated that *Jatropha* covered 500,000-600,000 ha across India. The second phase in the promotion of *Jatropha* on wasteland, as proposed by India's Planning Commission in 2003, includes expanding the plantation area of Jathropha to 12 million ha [4].

Even though the understanding of *Jatropha*'s biomass production and allometry [8,9], reproductive ecology [10,11] water use and footprint [12-14] significantly improved in recent years, the persistent lack of knowledge on input-responsiveness, agronomy and genetics mean that *Jatropha* as a biodiesel crop has yet to reach its full potential [15,16]. Studies on the environmental risks and benefits of the *Jatropha* biodiesel system have only recently become available [17-23].

Life cycle assessment (LCA) is the appropriate tool to unravel and quantify the potential environmental risks and benefits of biodiesel systems [24]. However, often LCA studies of biofuels are limited to energy and greenhouse gas balances [20,24-26] although other impact categories are important as well [23,27,28]. Several country or site-specific life cycle studies on *Jatropha* biodiesel (Thailand: [18,22]; Ivory Coast: [19]; Malaysia: [20] and China: [21]) show favorable greenhouse gas and energy balance compared to an alternative fossil fuel based system. For India a LCA study on *Jatropha* for electrification is available [23] showing a reduction of the life cycle GHG emissions by a factor 7 compared to a diesel generator or grid connection. When taking into account other environmental dimensions, the overall environmental performance only slightly improves compared to the reference system [23].

Based on high expectations created by the recent hype around biofuels and the resulting rapid expansion of *Jatropha* worldwide [29], there are voices suggesting that *Jatropha* is appropriate for small-scale, community based production aimed at local use. Large-scale investments [30] may hold both environmental and socio-economic sustainability risks, given the current knowledge gaps and the uncertain economic perspectives [30,31]. Small-scale initiatives allow us to assess the potential risks and benefits of the system and may pave the way to potentially sustainable expansion of *Jatropha* biodiesel production in the future. Based on this consideration, India's transportation biodiesel blending targets, and *Jatropha*'s potential role in meeting these, it was set out to evaluate the environmental performance of a transport fuel production system using *Jatropha* in rural India.

This paper presents a case specific LCA study for a small scale, low-input *Jatropha* biodiesel system in rural India that is being used for reclaiming wasteland and aimed at local consumption in transportation. The LCA compares the performance of the *Jatropha* system with a fossil fuel based reference system. Our analysis goes beyond assessing energy outputs and greenhouse gas balances and includes assessing other environmental impacts, particularly with respect to acidification, eutrophication and land use. This analysis adds to the growing body of knowledge by looking at using *Jatropha* biodiesel as a source of rural energy for transportation. In addition to the LCA of the current situation in the case study area of *Jatropha* for biofuel, the environmental impacts of incorporating a biogas installation for digestion of the *Jatropha* seed cake was simulated for a more comprehensive analysis.

2. Methodology

The total environmental impact of the complete production system was assessed using LCA according to the standard described by the International Organization for Standardization (ISO 14010/44:2006).

2.1. Goal, scope and system boundaries

This LCA is aimed at assessing impacts in five impact categories: (i) non-renewable energy requirement (NRER) [MJ], (ii) global warming potential (GWP) [CO_2-eq.], (iii) eutrophication potential (EP) [O_2-eq.], (iv) acidification potential (AP) [SO_2-eq.] and (v) land use impact on ecosystem quality (according to Achten et al. [32]). Additional to the NRER, a life cycle energy analysis was performed following Prueksakorn & Gheewala and

Pleanjai & Gheewala [18,33]. Both Net Energy Gain (NEG= energy output – energy input) and Net Energy Ratio (NER = energy output/energy input) were calculated. The latter is an accepted indicator for the energy efficiency of the system [18]. Carbon stock change (e.g. carbon debt [34]) due to land use change triggered by *Jatropha* cultivation is not included because of lack of data on carbon stored in the *Jatropha* plantations and in the former land use.

The system that was analyzed included *Jatropha* cultivation, oil extraction, biodiesel production (transesterification) and transportation, infrastructure and maintenance and by-products at all stages of the production process (Figure 1). The data used were collected from (i) mature plantations and a biodiesel factory in Allahabad, India, (ii) scientific literature and (iii) LCA databases. The allocation of environmental burdens to by-products was avoided by using system boundary expansion [35,36], in which the by-products were substituted with products from the reference system. Assuming local use of the produced fuel and by-products, the system boundary expansion was based on the local situation (Figure 1). The assessed life cycle impacts were reported on the basis of a functional unit (FU), which was defined as the release of 1 MJ in a car engine fueled by *Jatropha* biodiesel (following Achten et al. [37]).

In addition to the Allahabad case study (C), the environmental performance of the incorporation of a biogas installation into the Allahabad case (C_{BG}) was modeled and evaluated. The installation would be installed next to the seed press and would be fed with the seed cake left over after oil extraction. The digester effluent would be brought back to the field as soil amendment (Figure 1). It was assumed that the biogas installation has a CH_4 leakage of 10% of the gas produced [38,39]. The construction of the biogas installation is not included in the system boundaries, because it is assumed to have a negligible effect on the overall impact. The biogas is assumed to be used as cooking fuel (e.g. in the NGO school kitchen), which replaces the use of fossil-based natural gas in the reference system.

Insert Figure 1

2.2. Life cycle inventory

2.2.1 Research area

This LCA evaluated a specific low intensity *Jatropha* production system in Allahabad, India. The district of Allahabad is located in the North-East of peninsular India, in the state of Uttar Pradesh, and extends from 24°45'N to 26°30'N and from 80°45'E to 82°30'E. The mean annual rainfall is 1027 mm, which fits well in *Jatropha*'s climatic growing conditions [40]. The monsoonal rains typically start at the end of June and last till September. The alluvial soils are classified as fluvisol. The district has been mined for clay for brick making for years, resulting in large degraded areas suffering from gully erosion. These areas are now unsuitable for agriculture and currently covered by degraded grassland (further called wasteland).

Throughout the district about 560 households cultivate *Jatropha*. The *Jatropha* cultivation is promoted and supported by the NGO 'Utthan', which started its *Jatropha* development program in 2003. The NGO also runs an oil extraction and biodiesel production unit and is planning to expand this setup with a biogas installation fed on seed cake. The NGO promotes low input *Jatropha* cultivation systems (block planting, live fence, windbreak, intercropping, etc.). This study focused on the low input *Jatropha* block plantations on wastelands. This system included chemical fertilizer use only at plantation establishment.

2.2.2 Data collection

Data was collected from Utthan, a local NGO in Allahabad. This included field observations, NGO field datasets, farmers' group discussion and expert interviews. Data from scientific literature and from a life cycle inventory database (GEMIS, Darmstadt, Germany, http://www.gemis.de/) was used as well. Generally the system-specific data (e.g. fertilizer use) (Table 1) were collected from the NGO Utthan, while general (e.g. field emission rates: N_2O: 1%, NH_3: 10% and N leaching: 30% of applied N were taken from IPCC default factors [38]) and background data (e.g. production impact of fertilizer) were collected from literature and databases. Literature and databases were also used to cross-check the quality of the system-specific data collected in Allahabad. The factors considered in this study are given in Table 2 (cultivation, oil extraction, biodiesel production and end use on the basis of per production phase). For each factor descriptive statistics (mean and standard deviation) of the collected data were calculated.

The means by which inputs were brought to the system and intermediate outputs transported between different systems phases also need to be accounted. The transport distances of the seedlings, fertilizers, seeds, equipment and machines were all estimated using Google® maps (Google, New York, USA) based on the origin of these items.

Insert table 1

Insert table 2

For the assessment of the land use impact of the *Jatropha* system on ecosystem quality, field measurements were necessary to quantify the ecosystem structural quality (ESQ) and ecosystem functional quality (EFQ) [32] of three land uses: the land use under investigation (i.e. *Jatropha* plantation), the previous land use (i.e. wasteland/degraded grassland) and the local potential natural vegetation (lPNV) (i.e. the natural vegetation that would develop locally over the long term without human intervention). Five square plots of 100 m^2 were established in a five year old *Jatropha* plantation (14 ha) and 10 square plots of 100 m^2 in the adjacent wasteland, which represented the previous land use. Each of the plots in the wasteland was within 100-400 m from the plantation border. Plots were established around points randomly indicated on a map only showing the plantation boundaries. As no patches of lPNV (Acacia forest) can be found in the area, general indicator scores for lPNV were extracted from a literature review [41]. For each plot the selected indicators were measured (see section 2.3 and Table 3).

Insert Table 3 [42]

2.2.3 Product output and fossil fuel reference system

For an appropriate life cycle comparison, the fossil fuel reference system (FRef I) should provide the same products and functions as the *Jatropha* biodiesel system. Thus, all products and by-products of the *Jatropha* system should be substituted in the reference system. Figure 1 gives the product quantities for the *Jatropha* system per FU and the substituting products for the reference system. The substitutions reflect the local situation. Glycerin was considered the only by-product because the other by-products (pruning waste, husks and seed cake) are brought back to the field as soil amendment and are not system outputs. In the reference system the glycerin is substituted by synthetically produced glycerin of similar quality (according to Wicke et al. [43]). In the C_{BG} model, methane (CH_4) is produced and is another output of the system. Therefore, the fossil reference system was adjusted as well (case FRef II; Figure 1). The inventory analysis of the reference system was constructed using data from the scientific literature.

2.3. Evaluation of environmental impacts

Table 4 gives an overview of the basic calculation methods for the environmental impacts. All calculations were performed in Matlab® (MathWorks, Natick, Massachusetts). The land use impact assessment according Achten et al. [32] assesses both impact from land use change (LUC) and land occupation (LO) on ecosystem quality. The methodology [32] proposes several mid-point indicators suitable for this quantification. Among these total above-ground biomass (TAB) [kg dry matter ha^{-1}] and number of vascular plant species (NS) to quantify ESQ and soil cover (SC) [%], water infiltration rate (IR) [cm hr^{-1}] and vertical space distribution (VSD) (= dominant vegetation height divided by the number of vegetation strata) [m] to quantify EFQ were selected, based on measurement feasibility. The impact on the ecosystem quality is quantified by two end point indicators: ecosystem structural quality (ESQ) and ecosystem functional quality (EFQ).

$$ESQ = \left(\frac{\left(TAB_{ref} - TAB_{Jatropha}\right)}{TAB_{lPNV}} + \frac{\left(NS_{ref} - NS_{Jatropha}\right)}{NS_{lPNV}} \right) / 2 * 100 \quad \text{[eq. 1]}$$

$$EFQ = \left(\frac{\left(SC_{ref} - SC_{Jatropha}\right)}{SC_{lPNV}} + \frac{\left(IR_{ref} - IR_{Jatropha}\right)}{IR_{lPNV}} + \frac{\left(VSD_{ref} - VSD_{Jatropha}\right)}{VSD_{lPNV}} \right) / 3 * 100 \quad \text{[eq.2]}$$

with TAB, NS, SC, IR and VSD are the average mid-point indicator values for the *Jatropha* plantation, the lPNV and the reference land use which is degraded grassland for LUC impact and the lPNV for LO impact.

Insert Table 4

2.4. Life cycle interpretation

2.4.1 Completeness check

The completeness check was carried out by comparing the collected data with the data available in the literature and by expert interviewing. At this point the iterative process of defining the system boundaries was completed.

2.4.2 Uncertainty analysis

The uncertainty analysis was performed with a Monte Carlo analysis under the assumption of normal distribution for all variables. Results for the five impact categories were calculated 10 000 times by randomly selecting a value for each input variable based on their averages and standard deviations.

3. Results and discussion

3.1. Production system

This section describes the analyzed production system, based on the data gathered at NGO Utthan, Allahabad. Seedlings are prepared in the nursery using poly bags. Seeds are planted in a mixture of local compost and soil and are watered manually (water is pumped with an electrical pump). To prepare the wasteland for cultivation the field is ploughed with a tractor and planting pits are dug. 2599 *Jatropha* seedlings are planted per ha. During plantation establishment 111 kg ha^{-1} Urea (N:P:K: 46:0:0 [44]) and 111 kg ha^{-1} diammonium phosphate (N:P:K: 18:46:0 [44]), are applied in the planting pits. After plantation establishment no inorganic fertilizers are used. All biomass residues from pruning, dehulling and oil extraction are brought back to the field (Figure 1). Irrigation is practiced only in extreme circumstances when monsoon is late, and is done manually (about 15000 l ha^{-1} yr^{-1}). Over the rotation period, which was assumed to be 20 years, a mean yield of 1695 kg dry seeds ha^{-1} is expected. The extraction unit contains a boiler, an electric screw press and filter press and yields 275 kg crude *Jatropha* oil per 1000 kg seed. During transesterification 20 kg methanol and 0.84 kg NaOH is used per 100 kg crude *Jatropha* oil. The reaction takes place in a heated tank (60-80°C) and yields 18 kg glycerin and 97 kg *Jatropha* biodiesel. The glycerin is sold on the market in Allahabad.

3.2. Energy analysis

3.1.1 Non-renewable energy requirement

For production and use of one FU on average 222.0 (±10.5) kJ of non-renewable energy is required for the *Jatropha* system, which is a reduction of 82% compared to the reference system (Figure 2; basic figures in Table 5). This reduction is 8% more than the reduction found by Xunmin et al. [21]. The transesterification (48.9%) and the oil extraction (39.1%) steps are the biggest contributors to the energy requirement. The major contribution of the transformation process to the overall energy balance of the system confirms findings of other *Jatropha* LCA studies [19-21]. The cultivation phase represents only 12% of the non-renewable energy requirement, which is low compared to other biodiesel production systems (e.g., [18,20]), probably because this system has low fertilizer inputs. In the transesterification step, the production and use of methanol is the biggest energy consumer (46%). For oil extraction, the electrical energy to operate the boiler, expeller and filter press is produced with fossil fuel and made up the largest contribution (60.9%) to this part of the process. Over the whole life cycle, construction and maintenance of machinery accounts for 25% of the total NRER, while transportation contributes 3%. This contribution is low (e.g., compared to Prueksakorn & Gheewala, Lam et al. and Pleanjai & Gheewala [18,20,33]), since the Allahabad system has low levels of inputs and aims at local use of the products. This results in low transportation distances [t.km], both for bringing inputs to the system as for distributing outputs to the market. Adding a biogas installation to the system does not significantly influence the NRER per FU.

Insert table 5

3.1.2 Net Energy Gain and Net Energy Ratio

Considering all products, including biodiesel and glycerin, and based on the energy content of these products, the NEG is 188.7 (±45.2) kJ per FU while the NER is 1.85 (±0.22) (basic figures in Table 6). The NER is comparable to the results obtained for *Jatropha* biodiesel in Malaysia (1.92) [20] and China (2.0) [21], but is much lower than the findings in Ivory Coast (4.7) [19] and Thailand (6.0) [18,22]. These big differences are caused by the selection of by-products which are considered as 'energy output'. In our study only glycerin is considered a by-product to the *Jatropha* biodiesel, while the Thai studies also consider the energy contained in the wood as an output [18,22]. If only *Jatropha* biodiesel is considered as system output, the NEG is 78.2 (±25.0) kJ per FU and NER is 1.35 (±0.13) which is similar to the Thai findings (1.4-1.42) [18,22]. Compared to oil palm biodiesel systems (NER = 2.27-5.70) [20,33,37,45,46], the Allahabad *Jatropha* system shows lower energy efficiency.

In the case study where the *Jatropha* system is expanded to include a biogas installation, the NEG increases to 530.3 (±121.0) kJ per FU and the NER to 3.40 (±0.58), if all products and by-products are considered. Taking into account only the biodiesel and biogas output the NEG is 419.1 (±114.1) kJ and the NER is 2.89 (±0.54). These results show that including biogas production from seed cake considerably increases the energy efficiency of the *Jatropha* biodiesel system.

Insert Table 6

3.3. Global warming potential

The *Jatropha* biodiesel case study showed an emission of 123.7 (± 34.2) g CO_2-eq FU^{-1}, which is a 55±16% reduction in GWP compared to the reference system (Figure 2; basic data in Table 7). This result fits within the range of reductions available in literature (49-72%) [19,21]. The cultivation step is the biggest contributor in the system (86%), and the majority of these emissions are due to N_2O, which confirms previous studies [17,19]. The N_2O emissions are associated with N application in organic waste that is returned to the field. Because there are no field studies, this study relied on IPCC default values for this result, but due to the semi-arid nature of the environment, it is reasonable to expect that this estimate is an upper bound. The transesterification process contributes 11% to the total GWP of the *Jatropha* biodiesel system of which 83% is caused by methanol production.

Comparison with reductions attained by other biofuel systems (oil palm biodiesel: 38-79% [25,26,37,47,48]; biodiesel from sunflower, soy and rapeseed: 40-65% [24]; E85 Swichgrass ethanol (57%) [49], E85 Corn Stover ethanol (65%) [49] and Soybean based fuels (57-74%) [50]) puts the Allahabad *Jatropha* system at the lower end of the range of GWP reductions for biofuels.

In the case where a biogas installation that used seed cake as the feed stock was added to biodiesel production system, the GWP of the system increased to 159.4 (± 34.4) g CO_2-eq FU^{-1}; the primary source of additional emissions were CH_4 leaks in the installation (10%) [38]. The increase was not significant and the system achieved a similar reduction in GWP (51±14%) compared to the reference system as the system without biogas production.

Insert Figure 2

3.4. Other environmental impact categories

The *Jatropha* system showed an increase in AP of 49% compared to the reference system (Figure 2). The biggest contributions are made during the cultivation step, where 62% of the total AP is associated with NH_3 emissions and 37% is due to the combustion of the biodiesel product. The expansion of the *Jatropha* system with a biogas installation has no significant effect on the AP, or on the composition of the contributions.

The EP of the *Jatropha* case system is 430% higher than the EP of the reference system (Figure 2). 84% of the total EP of the *Jatropha* biodiesel systems is caused during the cultivation phase. Within the cultivation phase, the nitrogen leaching is the most important contributor to the EP (75%). The combustion of the biodiesel during its end use represents 16% of the total EP. The production of biogas from the seed cake has no significant effect on the EP, or on the composition of the contributions.

Changing waste land to *Jatropha* triggers an improvement of the ESQ (impact of -14.6 ± 9.3%) but a reduction in EFQ (impact of 24.0 ± 8.9%) (Figure 3). The improving ESQ means that the *Jatropha* plantation has a higher storage capacity in terms of biomass, structure and biodiversity than the wasteland The decreasing EFQ means that the *Jatropha* plantation has less control over water, material and nutrient fluxes than the wasteland (see [51] and [32]). This latter is mainly triggered by the impact on the infiltration rate. The wasteland shows higher infiltration rate (14.0±0.6 cm hr^{-1} against 3.3±0.1 cm hr^{-1} in the

Jatropha plantation) and the continuous herbaceous layer provides better soil cover (82±11% against 28±4.5% in *Jatropha* plantation) which reduces runoff. The land occupation impact of *Jatropha* block plantations shows an ESQ reduction of 55.4 ± 9.4% and an EFQ reduction of 66.1 ± 11.4% compared to the potential natural vegetation. These land use impacts apply to 0.55 $m^2yr\ FU^{-1}$.

Insert figure 3

3.5. Life cycle interpretation

The LCA results of this case study show similar trends to those found in analyses of other biofuels: NRER and GWP are lower compared to fossil fuel reference systems; AP and EP are higher than reference systems [47]. The increased acidification and eutrophication is the result of nitrogen related burdens during cultivation, confirming the study by Kim & Dale [47].

Although the energy and the global warming potential of this *Jatropha* system are moderate compared to other systems described in literature, it should be noted that this system is being operated on clay mined, unproductive land. Although the *Jatropha* system under research is a low input system, the inputs might be considered relatively high in relation to the outputs. This would trigger relatively higher environmental burdens per functional unit and, as such, lower NRER and GWP reductions compared to other biofuel systems. Further it deserves attention that in this case there is no direct land use conflict with food production. Indirect land use change effects might arise from exclusion of grazing animals from the plantations. However, based on the specific rural context and the scale of the intervention, this indirect impact can be considered negligible. Furthermore, carbon debts created by land use change in these wastelands are likely to be small.

The impact of the land use change from wasteland to *Jatropha* plantation further indicates an improvement in ESQ. However, it reduces the EFQ, which means that the ecosystem has less possibility to provide environmental services (see [51] and [32]). Expanding *Jatropha* plantation will bring an improvement in structural quality (ESQ), but, due to the permanent nature of agricultural management, it shows lower capacity (EFQ) to increase its quality beyond this point because it will never return to the state of lPNV. This is because generally an increasing ESQ would trigger an increase EFQ these results might look inconsistent or contradictory, but this is not the case. In case the *Jatropha* plantation would be established and then left to grow unmanaged, both ESQ and EFQ would increase. However, in this case, the *Jatropha* plantation will stay under management, increasing the ESQ but lowering the EFQ of the land. In other words, the wasteland shows lower structural quality (ESQ) than a *Jatropha* plantation, but hosts higher capacity to increase its quality, even beyond the quality of the plantation in case renaturalization towards the lPNV is possible. However, it will take a very long time for the wasteland to achieve similar structural quality as that achieved through planting *Jatropha*. It is the ecosystem approach of the used land use impact method [32] which allows these considerations.

Francis et al. [6] estimated the total wasteland area in India at 63.85 million ha. This area would suffice for the *Jatropha* expansion planned by the Indian Planning Commission. However, the estimate of Francis et al. also contains ‘underutilised/degraded/notified forest land’ (14.06 million ha), ‘degraded land under plantation crop’ (0.58 million ha) and ‘shifting cultivation’ (3.5 million ha) which could possibly imply carbon debts, or social and cultural conflicts. Looking at ‘gullied and/or ravined land’ (2.10 million ha) and ‘degraded pasture/grazing land’ (2.60 million ha), in the line of the wasteland investigated in this paper, a total wasteland area of 4.70 million ha would be available. A potential of 19.4 million ha lies in ‘land with or without scrub [sic]’ [6]

Adding a biogas installation to a *Jatropha* system increases the energy efficiency of the system, but has no significant influence on the NRER or the GWP reduction. The NRER is not influenced because the construction of the biogas installation itself is not included in the system boundaries and because the biogas installation would be installed next to the oil expelling unit, not triggering extra transportation steps. By producing biogas to reduce fossil energy use, an extra GHG emission is triggered by CH_4 leaking to the atmosphere. This indicated that the inclusion of a biogas installation represents a trade-off. In this case the GWP of producing biogas (physical CH_4 leaks from the digester) is similar to the GWP of producing and using natural gas in the reference system, which results in insignificant changes in GWP. In this study the CH_4 loss is based on IPCC values (as in Pathak et al. [39]). However, by using proper fittings, advance digesting technology, and proper digester management, CH_4 leaks can be reduced down to 1.5-3% [52]. In such cases, the addition of a biogas installation would yield a GWP reduction of 60-61% in comparison to the reference system (instead of 51%). In that case the installation of a biogas digester would result in an extra GWP reduction compared to the current situation (54%).

The contributions of the different production phases to the impact categories show that the most important portions of emissions to the atmosphere, soil and water are linked to the fertilizer and organic waste applications. The N_2O emissions (linked to fertilizer use) is the biggest share in the impact on GWP of the *Jatropha* systems. Also the AP is dominated by the NH_3 emissions due to fertilizer application. Through the leaching of N, fertilizer use is the biggest contributor to the impact on EP. Therefore fertilizer use, and in extension, the whole *Jatropha* cultivation hosts strong potential options for improvement. Optimization in cultivation practices and genetic selection are expected to minimize environmental impacts (also see [23]). The results of adding a biogas installation to the *Jatropha* system shows that the efficient use of the by-products as energy carrier hosts improvement potential as well, which confirms earlier findings [17,53]. However, our results also show that this issue has to be handled with precaution and that there is still need for further research on the optimal pathways to use the by-products. Furthermore, technological advances in cultivation (e.g., genetic selection), oil extraction (e.g. extraction efficiency) and transesterification (e.g. use of bioethanol [54]) offer options for improvement of system performance.

Some results show large standard deviations, which reflects the uncertainty on the input data. This is typical for a new system as *Jatropha* biodiesel for which scientific data are scarce and variable [53].

4. Conclusions

In general the small-scale *Jatropha* biodiesel system for local transportation use follows similar trends in environmental performance as other biofuel systems. Compared to other systems our case study shows a strong reduction in non-renewable energy requirement and a moderate reduction in global warming potential. The trade-off environmental cost for these reductions is an increase in eutrophication and acidification.

Expanding the *Jatropha* biodiesel system with biogas production enhances the energy efficiency while other impacts remain stable due to other offsetting factors. As fertilizer and waste applications (mainly N) are important contributors in most impact categories, optimizing fertilization and agronomic practices and improving crop uniformity through breeding are seen as the major system improvement options, along with the efficient use of by-products and technological advances.

Although this *Jatropha* system for local use shows some promising LCA results, it has to be noted that these reflect environmental performance and not complete sustainability. The study does not consider socio-economic impacts. Even though the *Jatropha* cultivation on wasteland does not trigger direct (or even indirect) competition with food and is expected to create only low carbon debt it might still compete with other resources (e.g. labour, water, etc.). However a small scale, low input system creates income generation opportunities [30]. Hence, this study is a partial contribution to increase insight in the sustainability potential of *Jatropha* based biodiesel systems.

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Glossary

AP	Acidification Potential
CJO	Crude *Jatropha* Oil
EFQ	Ecosystem Functional Quality
EP	Eutrophication Potential
ESQ	Ecosystem Structural Quality
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
IR	Infiltration Rate
LCA	Life Cycle Assessment
LO	Land Occupation
lPNV	local Potential Natrual Vegetation
LUC	Land Use Change
NEG	Net Energy Gain
NER	Net Energy Ratio
NRER	Non-Renewable Energy Requirement
NS	Number of vascular plant Species
SC	Soil Cover
TAB	Total Aboveground Biomass
VSD	Vertical Space Distribution

Figure captions

Figure 1. System boundaries of the *Jatropha* system, the Reference system and the system boundary expansion including product quantities per FU (CJO: crude *Jatropha* oil). *: Only applicable in C_{BG} scenario and FRef.II.

Figure 2. Impact of *Jatropha* biodiesel production and use in the Allahabad case on non-renewable energy requirement (NRER), global warming potential (GWP), acidification impact (AI) and eutrophication impact (EI).

Figure 3. Land use change and land occupation impact of *Jatropha* cultivation on ecosystem quality (EQ) [% of EQ increase or decrease compared to the local potential natural vegetation]. Negative values represent an EQ increase. Land use change is the shift from waste land to *Jatropha* plantation. (ESQ = ecosystem structural quality; EFQ = ecosystem functional quality).

Table 1. System specific information collected from NGO Utthan in Allahabad through field observations, NGO field datasets, farmers' group discussion and expert interviews

	Variables	**note**
Cultivation	nursery practices:	polybag use, water use, fertilizer use, machinery use
	field preparation	
	plantation establishment:	seedlings per ha, fertilizer use
	Plantation management:	irrigation, fertilization, weeding and harvest practices
	yield	kg seeds ha^{-1} yr^{-1}
	Origin of inputs	machinery, ferilizer
	Transport distances	inputs to field, seeds to processing unit
	Irrigation pump	capacity and energy consumption
Oil extraction	extraction rate	kg oil kg $seed^{-1}$
	boiler	capacity and energy consumption
	oil press	capacity and energy consumption
	filter press	capacity and energy consumption
	by-product use	seed cake
Biodiesel production	Transesterification practices	reagens and catalyst use
	by-product use	glycerine

Table 2. Overview of factors considered in the LCA of *Jatropha* biodiesel for transportation per production phase per impact category

	Cultivation	**Oil extraction**	**Biodiesel production**	**End Use**
NRER	(non-renewable energy requirement [MJ] for:			
	Tractor production	Oil press production	Transesterification unit production	
	Pump production	Electricity production and use:	Production methanol	
	Infrastructure: farm shed	- oil press	Production catalyst (NaOH)	
	Poly bags production	- filter press	Electricity production and use:	
	Fertilizer production		- transesterification unit	
	Diesel production and use*			
	Electricity production and use:			
	- pump			
GWP	Greenhouse gas emissions (CO_2, CH_4 en N_2O) [CO_2-eq] caused by:			
	Polybags production	Electricity production and use:	Methanol production	
	Burning waste polybags	- oil press	Electricity production and use:	
	Fertilizer production	- filter press	- transesterification unit	
	Fertilizer application			
	- organic	Biogas leakage†		
	- inorganic			
	Diesel production and use*			
	Electricity production and use			
	- pump			
AI	NH_3, NO_X and SO_X emissions to air [SO_2-eq] caused by:			
	N volatilization	Electricity production and use	Electricity production and use	biodiesel combustion
	poly bag burning	- oil press	- transesterification unit	
	diesel use*	- filter press		
EI	Nitrogen emissions to water and air (NH_3, NO_x) [O_2-eq] caused by:			
	N leaching	Electricity production and use	Electricity production and use	biodiesel combustion
	N volatilization	- oil press	- transesterification unit	
	poly bag burning	- filter press		
	diesel use*			

* Transport of machinery, transport of fertilizer, consumption of machinery, transport of seeds
† in biogas scenario C_{BG}

Table 3. Mid-point indicator measurement method for land use impact of *Jatropha* on ecosystem quality

Indicator	**Measuring method**
Total abovegroud biomass [kg dry matter ha^{-1}]	For the *Jatropha* plantation an allometric relation [9] is used, based on basal branch diameters measured for each branch of each individual in the plot. For the degraded grassland an estimate was based on [42]*
# vascular plant species	Counting number of vascular plant species that are present in each plot
Soil cover [%]	visual estimate of each plot
Infiltration rate [cm hr^{-1}]	Three double ring infiltrometer measurements per plot
Vertical space distribution [m]	Measuring dominant vegetation height with clinometer, divided by the number of vegetation strata present, per plot

*: own measurements were not possible

Table 4. Overview of evaluated environmental impacts, basic calculation method and unit

	Impact calculation	Unit
Energy		
non-renewable Energy Requirement	sum of fossil energy required throughout the life cycle	kJ FU^{-1}
Net Energy Gain	total energy output* – total energy input†	kJ FU^{-1}
Net Energy Ratio	total energy output† / total energy input*	-
Global Warming Potential	sum of GHG emissions‡ throughout the life cycle	g CO_2-eq FU^{-1}
Acidification Potential	sum of NH_3, NO_x and SO_x emissions throughout the life cycle	g SO_2-eq FU^{-1}
Eutrophication Potential	sum of nitrogen emissions and flows to water ways, groundwater and air	g O_2-eq FU^{-1}
Land use impact		
on ecosystem structural quality (ESQ)	Eq. 1	% for area×time FU^{-1}
on ecosystem functional quality (EQ)	Eq. 2	% for area×time FU^{-1}

* total energy input is based on the life cycle inventory

† total energy output is based on the energy content of the products and by-products

‡ GHG emissions: Greenhouse gas emissions in this analysis included CO_2, CH_4 and N_2O

Table 5. Life cycle non-renewable energy requirement (NRER) of *Jatropha* biodiesel for transportation FU^{-1} (FU = the release of 1 MJ in a car engine fueled by *Jatropha* biodiesel).

Production phase	Factor*	NRER [kJ]
Cultivation	Construction shed, tractor, pump	5.17±0.35
	Poly bag production	1.06±0.21
	Fertilizer production	13.13±0.47
	Diesel production and use	7.16±3.74
	Electricity production and use	0.18±0.02
	subtotal	**26.67±3.79**
Oil extraction	Construction oil press	29.08±5.32
	Electricity production and use	57.74±0.94
	subtotal	**86.82±5.41**
Biodiesel production	Construction transesterification unit	21.09±2.66
	Production methanol	50.25±0.34
	Production catalyst	1.98±0.50
	Electricity production and use	35.18±7.76
	subtotal	**108.49±8.22**
Total		**221.98±10.55**

* Factors correspond with Table 2

Table 6. Total energy input and energy output per functional unit and net energy gain (NEG) and net energy ratio (NER) of the case study and the model of the case with biogas production included (FU = the release of 1 MJ in a car engine fueled by *Jatropha* biodiesel).

Case	**Total energy input FU^{-1}** [kJ]	**Energy output FU^{-1}** [kJ]	
		Only biodiesel	Biodiesel and by-products
	222.0±10.5	300.2±22.8	410.7±44.0
NEG		78.2±25.0	188.7±45.2
NER		1.35±0.13	1.85±0.22

Case + Biogas	**Total energy input FU^{-1}** [kJ]	**Energy output FU^{-1}** [kJ]	
		Biodiesel + biogas	Biodiesel and by-products
	222.0±10.5	641.1±113.4	752.3±120.2
NEG		419.1±114.1	530.3±121.0
NER		2.89±0.54	3.40±0.58

Table 7. Life cycle global warming potential (GWP) [g CO2-eq] of *Jatropha* biodiesel for transportation FU^{-1} (FU = the release of 1 MJ in a car engine fueled by *Jatropha* biodiesel).

Production phase	Factor*	GWP
Cultivation	Polybags production and discharge	0.65±0.09
	Fertilizer production	1.00±0.22
	Fertilizer application (N_2O)	104.55±34.22
	Diesel production and use	0.44±0.09
	Electricity production and use	0.01±0.00
subtotal		**106.66±34.22**
Oil extraction	Electricity production and use	3.74±0.07
	Biogas leakage†	35.37±6.36
subtotal C		**3.74±0.07**
subtotal C_{BG}		**39.11±6.36**
Biodiesel production	Production methanol	11.06±0.53
	Electricity production and use	2.28±0.54
subtotal		**13.34±0.77**
Total C		**123.73±34.23**
Total C_{BG}		**159.36±34.41**

* Factors correspond with Table 2
† in biogas scenario C_{BG}

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