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*Research Article*

# Environmental Impacts of *Jatropha curcas* Biodiesel in India

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In the context of energy security, rural development and climate change, India actively promotes the cultivation of *Jatropha curcas*, a biodiesel feedstock which has been identified as suitable for achieving the Indian target of 20% biofuel blending by 2017. In this paper, we present results concerning the range of environmental impacts of different *Jatropha curcas* cultivation systems. Moreover, nine agronomic trials in Andhra Pradesh are analysed, in which the yield was measured as a function of different inputs such as water, fertilizer, pesticides, and arbuscular mycorrhizal fungi. Further, the environmental impact of the whole *Jatropha curcas* biodiesel value chain is benchmarked with fossil diesel, following the ISO 14040/44 life cycle assessment procedure. Overall, this study shows that the use of *Jatropha curcas* biodiesel generally reduces the global warming potential and the nonrenewable energy demand as compared to fossil diesel. On the other hand, the environmental impacts on acidification, ecotoxicity, eutrophication, and water depletion all showed increases. Key for reducing the environmental impact of *Jatropha curcas* biodiesel is the resource efficiency during crop cultivation (especially mineral fertilizer application) and the optimal site selection of the *Jatropha curcas* plantations.

## 1. Introduction

India relies heavily on crude oil imports, and this trend will continue due to the rapid growth of its economy and population. In order to foster energy security, India's strategy is to focus efforts toward energy self-reliance and developing renewable energy options. In this context, India proposed an indicative biofuel blending target of 20 percent for both bioethanol and biodiesel by 2017 (B20 target) [1].

Besides fostering India's energy security and combating climate change, another main driver was to increase the productivity of the estimated 55 million hectares of marginal land in India [2] and thus, provide additional employment to the vast rural population. *Jatropha curcas L.* was identified by the Indian government as one of the most suitable biodiesel feedstocks, since it is able to grow on marginal land and yields high-quality oil suitable for energetic use. India set an ambitious target of 11.2–13.4 million hectares to be planted with *J. curcas* by 2012 [3].

However, even if *J. curcas* is promoted on marginal land, there will be a displacement of existing land use patterns, including activities such as livestock grazing and gathering of wild products conducted by local communities [4]. The loss of related ecosystem services affects particularly subsistence farmers and the rural poor. On the other hand, *J. curcas* has the ability to prevent desertification [5] and to improve the ecosystem function of marginal land [6].

Several studies have underlined that using *J. curcas* biodiesel reduces greenhouse gas (GHG) emissions by about 8 to 88 percent compared to the use of fossil diesel [5–12]. However, if *J. curcas* is cultivated on former primary forest land, the impacts are most likely negative and lead to carbon debts [13].

Further, Reinhard and Achten concluded that *J. curcas* cultivation has a higher impact on acidification and eutrophication than the use of fossil fuels [6, 7]. Thus, the environmental burden might be shifted from global warming to other environmental impacts if biofuels are used instead of fossil fuels.

Although *J. curcas* has the potential to grow rain-fed in water scarce areas, irrigation may be applied for increased yields, and consequently use relatively large amounts of water compared to other biofuels [14]. Such practice would also lead to relatively high stress on water resources [15]. However, the different estimates of irrigation water consumption differ and may be low in most cases, requiring detailed assessment based on field data on yield and corresponding irrigation [16, 17].

The huge variation of the LCA results indicates that there is no general answer whether *J. curcas* production and use is environmentally sustainable or not. The performance highly depends on the former land use, the intensity of the cultivation, the efficiency of processing, and on the usage of *J. curcas* products and byproducts. However, the main environmental impact is generally caused during *J. curcas* cultivation [6].

The main objective of the study is to assess the range of environmental impacts of different *J. curcas* cultivation systems and to benchmark *J. curcas* methyl ester (JME) with fossil diesel. Therefore, nine agronomic trials in Andhra Pradesh are assessed, where the yield was measured as a function of different inputs such as water, fertilizer, pesticides, and arbuscular mycorrhizal (AM) fungi. Further, JME used for transport is compared to the use of fossil diesel according to the nonrenewable energy consumption, global warming potential, and other environmental impacts (eutrophication, acidification, ecotoxicity, water demand, and land use). Based on these results, the optimization potential of the *J. curcas* value chain will be determined.

## 2. Methods and Materials

*2.1. Study Site.* The agricultural trials were established in 2008 at TERI's experimental station at West Godavari, Andhra Pradesh, India. The area is situated at 17°00′N lat 81°10′E lon with an average daily temperature range of 22°C to 45°C. The annual precipitation is 1098 mm and the plantations are all established on red soil with sandy loam texture. Randomized block design was used for the experimental setup. The test plots are 81 $m^2$ in size and contain 9 plants. Figure 1 provides an overview on the 9 different test plots, where the yield response to water input, fertilizer (organic or mineral) and AM is assessed. A more detailed description of the *J. curcas* cultivation is provided in Section 3.2.

*2.2. Methodology.* The environmental impacts over the whole value chain were estimated using the life cycle assessment (LCA) approach. The study was designed according to the ISO standards 14040/44 [18, 19]. All the LCA calculations were done in SimaPro v7.3.3 [20].

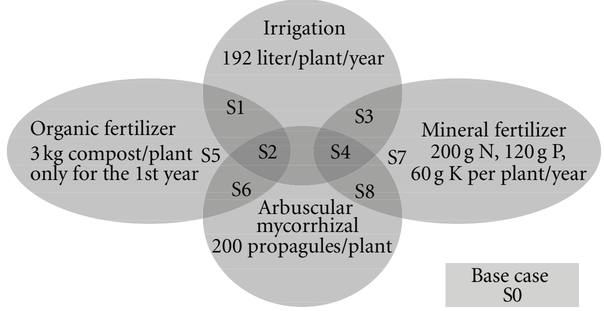


Figure 1: Overview showing the nine different agricultural trials (S0–S8) using different inputs.

*2.3. Functional Unit.* The performance of the different *J. curcas* production systems were compared per kilometre driven in New Delhi using an EURO3 standard passenger car with a fuel consumption of 2.37 MJ per kilometre [21].

*2.4. System Boundaries.* The assessment comprises all the relevant process stages, from cultivation, processing, transport of the fuel to the filling station, and the use of the fuel in the vehicle, including also the infrastructure. Further, the *J. curcas* value chain is benchmarked to the full life cycle of fossil fuel.

A system expansion approach according to the ISO standard is used to account for the substitution benefits of the byproducts in biodiesel production. *J. curcas* press cake is assumed to be substituted for mineral fertilizer due to the relatively high nutrient composition. Glycerine is assumed to be substituted for industrial glycerine. However, this assumption has to be changed if the glycerine market were saturated (i.e, if the B20 target was achieved). The husks and leaves of *J. curcas* are left on the field and thus stay within the modelled system. An overview showing the main processes of the compared systems is provided in Figure 2.

*2.5. Inventory Data.* Specific data for the cultivation of *J. curcas* was collected from the test plots in Andhra Pradesh, India. The inventory data for JME production and use was mainly derived from literature. The background data on energy supply, industrial processes, transportation and infrastructure were taken from ecoinvent v2.2 [22]. The Indian electricity mix was modelled according to Withaker and Heath [10].

*2.6. Environmental Impact Assessment.* The energy balance of the compared systems was measured according to the cumulated energy demand (CED) methodology [23]. For this study, only the amount of nonrenewable energy consumed (in MJ per kilometre) was considered.

The global warming potential (GWP) was assessed with a 100-year time horizon and is based on the characterization factors provided by IPCC [24]. It has to be noted that the carbon uptake during *J. curcas* cultivation is assumed to be equal to the biogenic carbon release during combustion and thus is not accounted for in the impact assessment.

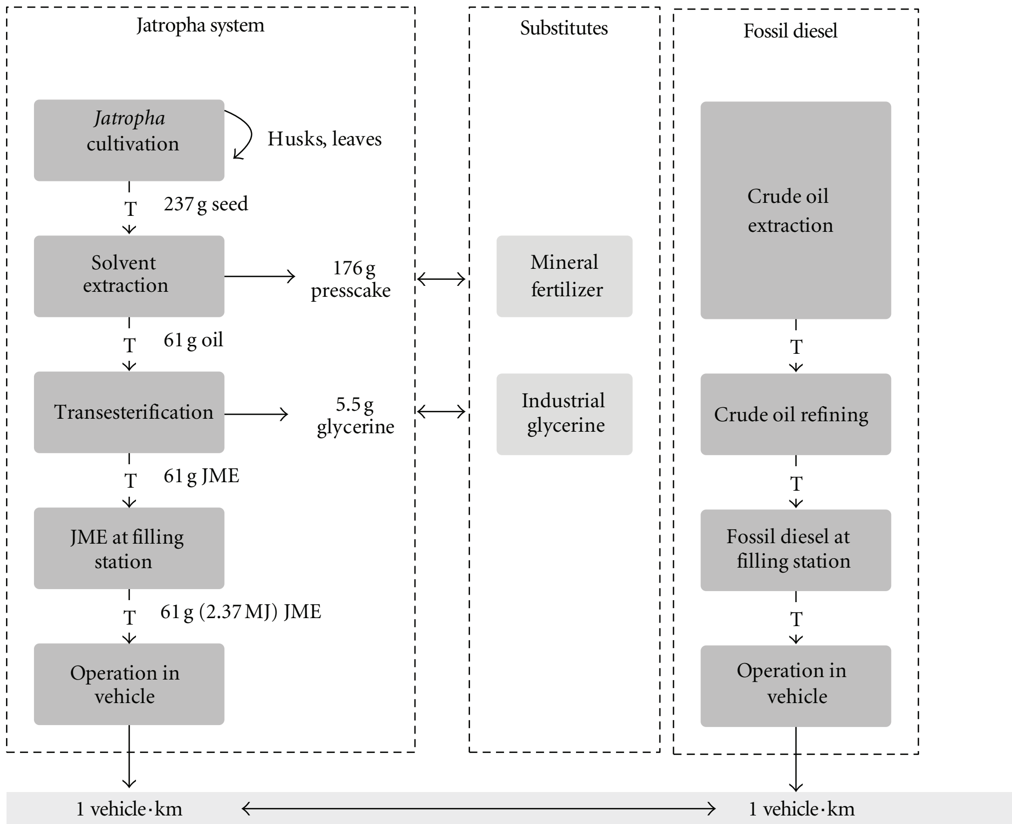


Figure 2: Flow diagram of the compared systems. All values refer to the functional unit of driving a default EURO 3 passenger car [21] for 1 km.

Since currently no specific impact assessment method for Indian environmental conditions was available, the midpoint impact categories of the Recipe methodology were used [25]. The ecotoxicity impacts were assessed based on the USEtox impact factors [26]. The cumulated water consumption over the whole life cycle was assessed for all value chains [25]. The regionalized impact of freshwater consumption, which is available on major watershed level [27], was qualitatively discussed. Table 1 provides a list of the characterization factors used.

## 3. Data Inventory

*3.1. Fossil Reference System.* India's largest fossil oil field is the offshore Mumbai High field. However, about 75% of India's crude oil is imported mainly from onshore oil wells from the Middle East and Africa [28]. The crude oil is assumed to be transported by a transoceanic tanker from Saudi Arabia and Mumbai High to the Visakhapatnam refinery in India, over a distance of 7,000 km, or 3,200 km respectively. From there the diesel is distributed to the regional filling stations by train (600 km) and truck (150 km). The inventory data for the diesel production was taken from Withaker and Heath [10] and was based on background data from ecoinvent v2.2 [22].

The lower heating value of fossil diesel is 42.8 MJ/kg and the fuel consumption of the EURO3 standard ecoinvent passenger car is 2.37 MJ/km [21]. The emission profile of combusting the diesel in the engine was taken from Zah et al. [29].

### *3.2. J. curcas Cultivation*

*3.2.1. Seed Material and Propagation. J. curcas* plants were prepared from the Chhattisgarh germplasm accession. The seedling production from seeds was carried out by pre-cultivation of *J. curcas* seedlings in polyethylene bags. Small black plastic bags were filled with soil and 200 propagules of AM fungi were added to the bag, where AM treatment was given. The AM fungi colonizes the root cortex in a mutualistic association, resulting in a bidirectional transfer of carbon from the plant to the fungus and of minerals, especially phosphorus, from the fungus to the plant [30, 31]. One seed was planted in each bag, and a survival rate of 80 percent was recorded.

*3.2.2. Cultivation System.* The seedlings were raised in nurseries for 3 months before they were planted with a spacing of 3 m × 3 m. Before plantation, the tillage of the land was prepared by a tractor, consuming about 12-litre diesel per hectare. For the trials using mineral fertilizer, 200 : 120 : 60 g

Table 1: Impact categories used in this study.

| Impact category | Unit | Source | Remarks |
|---|---|---|---|
| Cumulated energy demand | MJ non-renewable energy input | [23] | Only the non-renewable energy sources were considered (fossil and nuclear) |
| Global warming potential | Kg $CO_2$ eq. | [24] | Factors for GWP 100 years |
| Ecotoxicity | $CTU_e$ | [26] | Recommended factors for aquatic ecotoxicity |
| Terrestrial acidification | Kg $SO_2$ eq. | [25] | World average factors |
| Freshwater eutrophication | Kg P eq. | [25] | Generic factor |
| Water consumption | $m^3$ water consumption | [25] | Only blue water consumption was considered |
| Land occupation | $m^2$ land occupied | [25] | |

of N : P : K were applied per plant and year. For the trials using organic fertilizer, three kg of aerobic compost (1.88% available N, 2.56% P, and 3.76% K) were applied per plant only at the time of plantation. Pesticides are applied prophylactically during the establishment of the *J. curcas* plantations. Per pit, 20 mL of Chlorpyrifos 20EC mixed with 2 L of water was applied, and the subsequent pesticide spraying was only repeated if required (e.g, due to high pest infestation). Within this study, pesticides are assumed to be applied every five years.

The $N_2O$, and $NO_x$ emissions to the air caused by the fertilizer application were calculated according to IPCC [32]. The $NH_3$ emissions were calculated based on the Agrammon emission factors (15% for urea and 80% of the total available nitrogen for compost) [33]. The nitrate and phosphorous emissions to ground-and surface-water were calculated according to Faist et al. [34], taking regionalized parameters such as the local climate and soil type into account. Further, the heavy metals contained in the fertilizer and the active ingredients of pesticides were considered as emissions to the soil [35].

The rain-fed trials were drip-irrigated only once during plantation of the saplings. Each plant of the irrigated trails (S1 to S4) was drip irrigated with 8 L water per week during 24 weeks.

Standard transportation distances according to ecoinvent v2.2 were assumed for all input materials from the regional storage to the site [36]. The weeding, pruning, and harvesting were conducted manually. The economic lifespan of a *J. curcas* tree was assumed to be 20 years.

*3.2.3. Land Use and Carbon Stock Change.* The agronomic trials were conducted on fertile land, where previously maize was cultivated. The land use shift from agricultural land to *J. curcas* plantations directly affects the carbon stock, but also has indirect effects. Within this study, the GHG emissions related to the direct land use change are quantified, and indirect effects are discussed qualitatively.

The carbon emissions from direct land use change were calculated according to the Tier 1 approach proposed by IPPC [32]. The carbon change was calculated as the difference of the carbon in above-ground biomass (AGB), below-ground biomass (BGB), dead organic matter (DOM) and soil organic carbon (SOC) before and after *J. curcas* plantation. The discounting period of land use change was set to 20 years.

According to IPCC, the AGB and BGB of annual agricultural crops, such as maize, is assumed to be zero, since it is harvested every year. The AGB of *J. curcas* plantations was calculated based on the harvesting index (36%) and the dry matter fraction of wood (25%) [37]. Due to the lack of data, we assumed that the harvesting index and the dry mass fractions were the same for all cultivation scenarios. The BGB was calculated using the root-to-shoot ratio of 0.41 and a carbon fraction of 0.47 [38]. The calculated carbon stock in this study is for intensive cultivation systems of about 10 ton carbon per hectare, which is very similar to the measured carbon stock of a *J. curcas* plantation in southern India [39]. The SOC content of the specific region is 34.2 t C/ha [40], but based on the findings of Bailis and McCarthy, the SOC change was assumed to be negligible [39].

*3.2.4. Yield.* The agronomic trials were established in 2008 and thus have not yet reached maturity. Since the yield increase in the upcoming years is unknown, low-, medium-, and high-yield scenarios were assessed. In the conservative low-yield scenario the yield is assumed to be equal to the yield of year three. For the medium yield, a yield increase of 15% in year four and 5% in year five is assumed. While the high-yield scenario assumes a yield increase of 30% in year four and 10% in year five.

*3.3. Oil Extraction.* After harvesting, the remaining seed husks are removed and brought back to the field. The *J. curcas* seeds are transported from the field to the oil extraction factory over a distance of 50 km by a 16 t lorry. The oil is extracted by cold pressing using an electric screw press [41] and purified by a bag filtration system [42]. The press has an oil expelling efficiency of 80%, and the filtration system has an efficiency of 92%. The oil content of the *J. curcas* seeds is 35%, resulting in a seed demand of 3.88 kg per kg purified oil. The expeller has a capacity of 175 kg seeds per hour and is powered by a 22 kW generator. The lifespan of the press is assumed to be 10 years, while it is operated 24 hours a day.

Per kg *J. curcas* oil also 2.88 kg of press cake is produced. The nutrient values of press cake are 2.2% N, 8.3% $P_2O_5$, and 3.3% $K_2O$ [37]. It is assumed that seed cake is used as a fertilizer, being substituting for the mineral fertilizers dominantly used in India, namely, potassium chloride, urea, and single super phosphate [43].

*3.4. Transestrification of J. curcas Oil.* For this study a base catalytic transesterification reaction [44] was modelled to produce JME out of *J. curcas* oil and methanol (134 kg per ton JME). The reaction was carried out in a continuous flow reactor with a capacity of 1000 L/h. The catalytic reaction was mediated by potassium hydroxide and a mass conversion efficiency from *J. curcas* oil to methyl ester of 100% is assumed. Besides JME glycerine is also produced as a byproduct. A mass fraction of 0.09 of glycerine in relation to JME was used and the glycerine is substituted for conventional glycerine.

*3.5. Use of J. curcas Methyl Ester.* JME is transported from the transesterification plant to the filling station by truck and train. The energy content of JME is 38.9 MJ per kg [45]. For this study, the same ecoinvent passenger car was assumed as for the fossil diesel transport. Since the efficiencies of the diesel B20 and B5 blends were similar to biodiesel and fossil diesel [46], the same fuel consumption as for the fossil diesel run vehicle of 2.37 MJ per km was assumed. However, the emissions were slightly different for biodiesel and fossil diesel. Generally the emissions such as CO and PHAs in an internal combustion engine are lower for biofuels than fossil fuels. However, $NO_x$ emissions are measured to be higher. The ecoinvent emission profile was adapted according to the values given by Jain and Sharma [46].

## 4. Results and Discussion

*4.1. Agronomic Practice and Yield Response.* Figure 3 shows that the yields are highly varying, ranging from about 0.4 to 0.6 t/ha for rain-fed plantations (S5 to S8) to 2 to 2.6 t/ha for irrigated *J. curcas* cultivation systems (S1 to S4). The figures of this study match the yield figures reported by Estrin as 0.67 t/ha poor rain-fed soil and 2.5 t/ha fertile irrigated soil in India [5]. However, the yields remain still below the widely expected productivity of 5 ton of seeds per hectare and more, which were based on extrapolations from single high yielding trees [47]. One reason for this is the insufficient systematic selection of genetic material and the lack of agronomic knowledge adapted to the different agroclimatic contexts.

The agronomic trials of this study indicate that the main yield increase under the conditions of the study site can be achieved with irrigation, followed by application of AM. By applying AM, the yield could be increased by 14% for intensive cultivation systems and by 4% for low-input cultivation systems. The yield response of only applying mineral fertilizer on relatively fertile land is marginal. As a consequence of the results, the application of mineral fertilizer on the test plots was stopped in 2011.

*4.2. Energy Balance and Fossil Fuel Savings.* Figure 4 shows the requirements of nonrenewable energy for the production of *J. curcas* biodiesel expressed as MJ per vehicle·km and compared with fossil diesel. The nonrenewable energy demand differ among the scenarios, ranging from almost zero (S0) to 160% (S7, low-yield scenario) compared with the fossil reference. The results are mainly determined by the resource efficiency of the cultivation phase (e.g, amount of mineral fertilizer per yield). Intensively managed *J. curcas* plantations (S3 and S4) consume about 2.2 MJ of nonrenewable energy per kilometre, which is 70% less than fossil fuels (7.1 MJ/km). For scenarios S7 and S8, the high amounts of mineral fertilizer applied and the relatively low-yield lead to the very high nonrenewable energy demand (7.4 MJ/km and 6.3 MJ/km resp.). However, the management practice for the trials S7 and S8 will not be implemented, since the provided nutrients exceed by far the nutrient demand from the low-yield plants. Due to the relatively low fertilizer input, scenarios in which organic fertilizers were applied only for the establishment of the plantation (S1, S2, S5, and S6) completely substitute fossil fuels.

Besides the cultivation practice, the substitution benefits of the press cake (1 MJ/km) and the glycerine (0.5 MJ/km) also influence the overall fossil energy demand of JME. Achten et al. showed that by using the press cake for biogas production, the nonrenewable energy demand of the JME value chain can be further reduced [6]. The JME production and the transport of the fuel to the filling station only consume about 0.9 MJ of fossil energy per km driven.

*4.3. Global Warming Potential.* Figure 5(a) summarizes the contribution of life cycle stages to global warming potential (GWP), measured in kg $CO_2$ equivalents. The GWP related to JME is in general lower than fossil diesel and sensitive to the agricultural phase, especially to the amount of mineral fertilizer applied and indirectly to the yield. Unmanaged cultivation systems are almost carbon neutral (S0), and low-input cultivation systems reduce the GWP by 95% (S1 and S2) and by 87% (S5 and S6), respectively as compared to fossil diesel. Intensive cultivation systems show a net GHG benefit of 38% (S3) to 46% (S4). In absolute terms, 178 g (S3) or 214 g (S4), respectively of $CO_2$ equivalent can be saved per kilometre driven. If the *J. curcas* plots are intensively managed, but not irrigated, the carbon benefit of using renewable energy carrier is overcompensated by GHG emissions caused through the fertilizer production (S7 and S8).

In general, the application of AM reduces the GWP, since the effect of the yield increase due to AM dominates over the GHG emissions caused during the AM production. The production, transport, and use of JME only show minor contributions to the overall impact, while the GHG emissions related to the processing are compensated for by the substitution effects of the byproducts.

In general, the GHG balance is sensitive to direct and indirect emissions of land transformation and occupation [48, 49]. Shifting the land use from low carbon stock land to a tree cultivation leads to a direct carbon stock increase and consequently to more GHG savings. Considering also the rise in carbon stock (Figure 5(b)), the GHG savings increase from 46% to 91% for intensive cultivation system (S4) and from 38% to 133% for rain-fed extensive systems (S6).

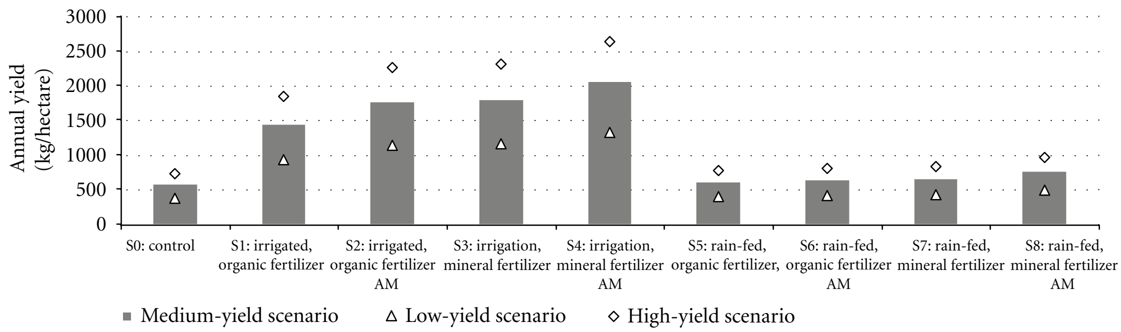


Figure 3: Medium yield of the different cultivation systems (S0 to S8) in kilogram per hectare. The annual productivity of the low- and high-yield scenarios is indicated by the triangle, and rhombus, respectively.

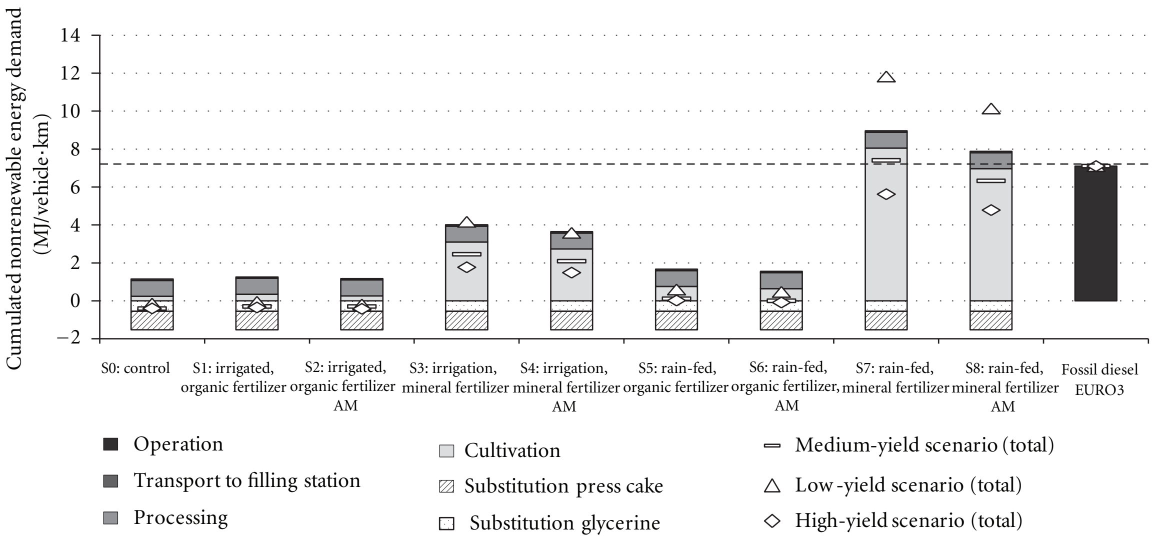


Figure 4: Cumulated nonrenewable energy demand of the different cultivation systems expressed as MJ per vehicle·km and compared with fossil diesel (dotted line). The total nonrenewable energy demand of the low-, medium- and high-yield scenarios are indicated, by the triangle, line segment, and rhombus, respectively.

However, besides the direct land use change, the former activity (maize cultivation) might be shifted to other areas, leading to a sequence of displacement. The indirect displacement can take place very locally, when neighbouring farmers start cultivating the displaced product in order to satisfy the demand of the local market. Displacement can also take place on a large-scale, if the displaced product is demanded additionally on a global market. Finally, the additional demand for agricultural area could either be satisfied by intensification of the production or it finally leads to an expansion into natural areas. Bailis and McCarthy judged that the carbon stock of *Prosopis juliflora* woodland in southern India has about the same carbon storage than *J. curcas* plantations [39]. Thus, the benefit of increase carbon stock from transforming maize to *J. curcas* plantation might be compensated for by indirect land use shifts. In any case, *J. curcas* cultivation is only environmentally sound if the plantations are established on low carbon stock land and indirect effects are actively mitigated by measures such as intensification.

*4.4. Other Environmental Impacts.* In Figure 6, the detailed characteristics of the environmental impact of a typical small-holder system with applying little organic fertilizer and water (S6), a typical intensive managed large-scale system (S4) and the cultivation system with the lowest GWP impacts (S2) is compared with the fossil reference. The maximum value for each impact category is set as the reference (100%) and thus the resulting patterns allow a relative comparison of the impact categories amongst the fuel systems. However, since the impact categories are not normalized and weighted against each other, no conclusion about the relevance of each impact category is drawn.

Conventional diesel causes generally higher GHG emissions and depletes more fossil fuels as compared to JME (see Sections 4.2 and 4.3). However, by using JME the environmental burden is shifted towards an increased impact on ecotoxicity, acidification, freshwater eutrophication as well as on water and land resources, mainly caused during the cultivation phase. The use of fertilizer, irrigation and application of pesticides (S6) generally leads to higher yields,

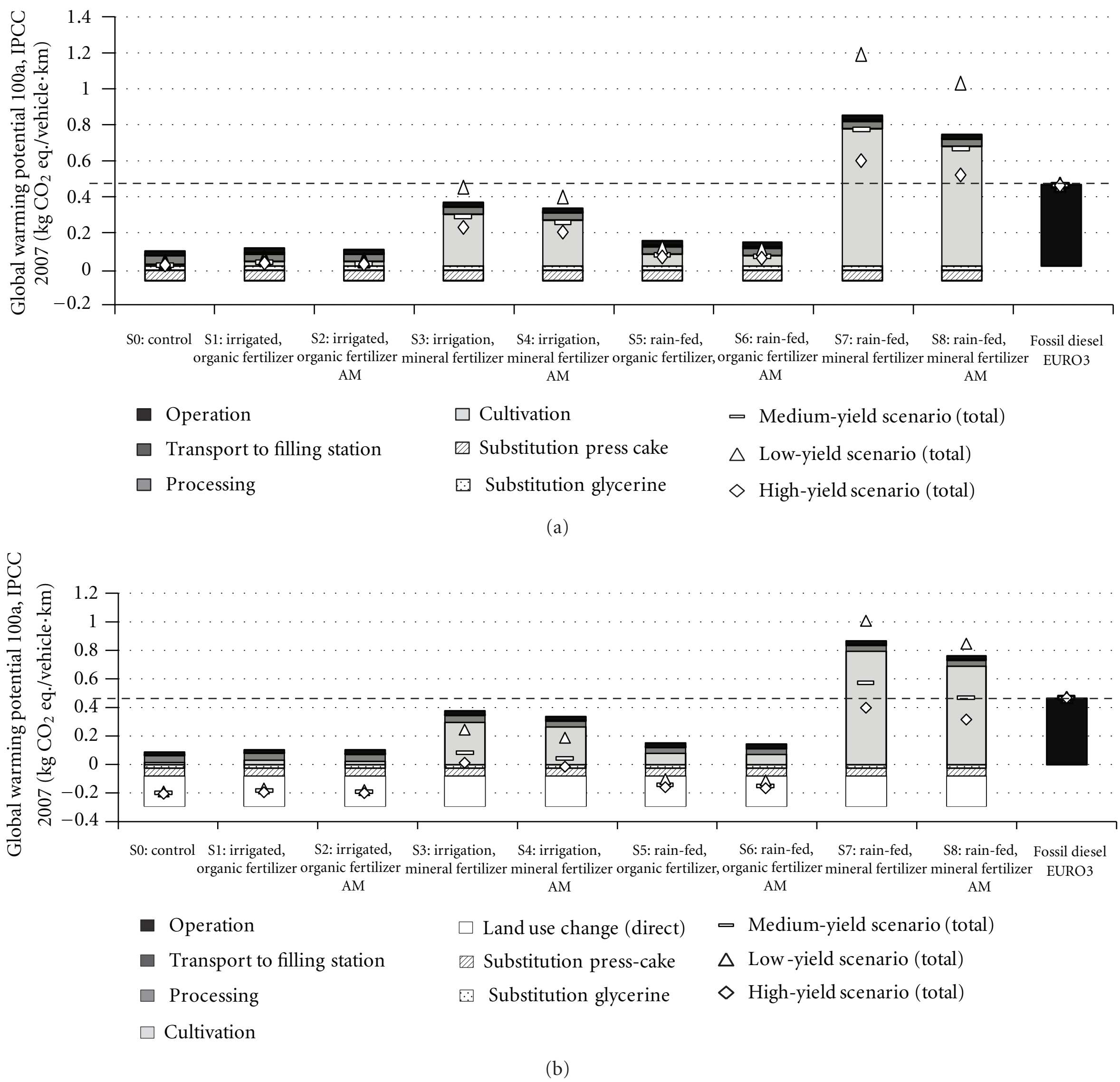


Figure 5: Global warming potential (GWP) of the different cultivation systems compared with fossil diesel (dotted line) expressed as kg $CO_2$ equivalent per vehicle·km, without (a) and with (b) direct emissions from land use change. The total impact of the low-, medium- and high-yield scenarios are indicated by the triangle, line segment, and rhombus, respectively.

but also to higher environmental impacts compared to low-input cultivation systems (S2 and S4).

The *terrestrial acidification* is mainly caused by the ammonia emissions related to fertilizing (91% of S4) and marginally by the combustion of the biofuel due to nitrogen oxide emissions. The acidification potential of fossil fuels over the whole life cycle is significantly smaller (e.g, 10.2 times smaller than S4) and is mainly caused by the release of nitrogen oxide and sulfur oxide during the refining and the combustion process in the engine.

The *ecotoxic effect* of the compared *J. curcas* value chains is mainly caused by the pesticide application and is for intensive *J. curcas* cultivation systems by a factor of 27 (S4) and for extensive systems by a factor of 18 (S6) and 7 (S2) higher than for fossil diesel.

For irrigated cultivation systems, driving one kilometre is linked to a blue *water consumption* of 24 litres (S4) or 26 litres (S2) respectively over the whole life cycle. JME based on low-input *J. curcas* cultivation system (S6) and fossil diesel only consume 1.4 or 0.6 litre respectively of blue water per km over the whole life cycle. Even though the yield response to irrigation during the dry period is high (see Figure 4), the application of water increases the resource competition between biofuel plantations and food crops, since the water stress in India is relatively high [27, 50]. The water consumption/deprivation indicator only takes the amount of blue water consumed over the whole life cycle into account. The land use change from maize to a tree plantation, however, does directly affect the hydrology through the change of evapotranspiration regime, as permanent crops

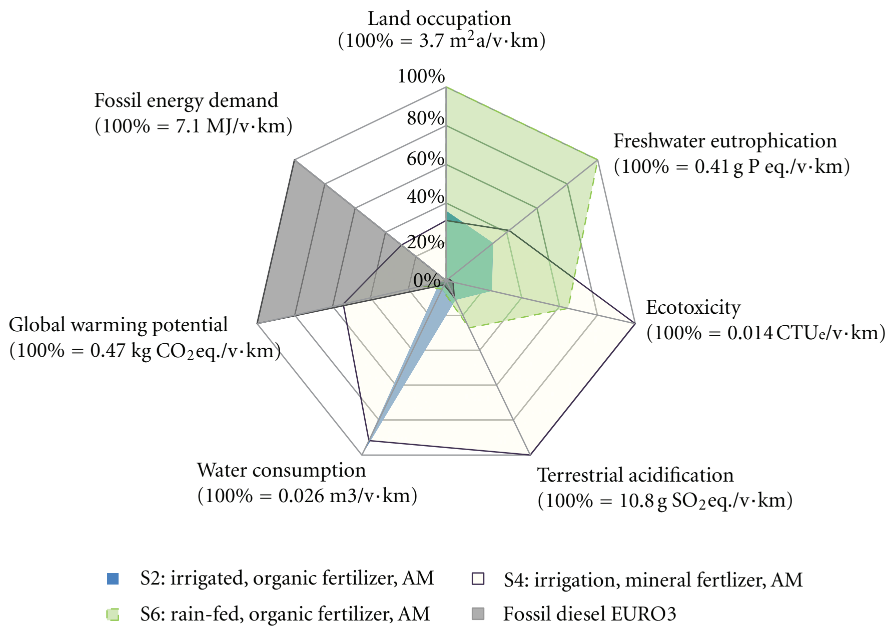


FIGURE 6: Mid-point indicators of different *J. curcas* scenarios (S4 and S6) and the fossil reference per vehicle·km in a relative scale.

with elaborated roots can use more rain water. This effect is not accounted for within this study.

The *J. curcas* value chains show a relatively high eutrophication effect compared to fossil fuels. The *eutrophication* is mainly caused by phosphorous emissions to surface water due to soil erosion. Soil erosion is in general higher on cultivated land than for natural ecosystems. However, due to the lateral rooting system of *J. curcas* which stabilizes the superficial soil, less soil erosion can be expected compared to the former land use (maize). The low-input management practice (S2 and S6) reduces the eutrophication impact per hectare. However, if the yields are low, the eutrophication impact for low-input system per kg seeds produced can be higher than in intensive cultivation systems (S6).

In addition, low-input cultivation systems also provide low-yields, and thus more *land* is required to achieve the B20 target. The rain-fed cultivation system with little inputs (S6) demands for about 3.7 $m^2$ of land per kilometre driven, while the intensive scenario (S4) only occupies 1.2 $m^2$ of land per kilometre driven. In order to substitute 20% of India's diesel consumption, 10.2 million tons of biodiesel are required and to substitute 20% of the diesel used for transportation, 6.9 million tons of biodiesel are required [51]. Thus, the achievement of the B20 target would require 13.1 (S4) to 42.3 million (S6) hectares of land under *J. curcas* cultivation. However, JME does not substitute for 100% of fossil fuels, since its production requires a certain amount of fossil fuels to, for example, transportation or fertilizer production. Considering this factor, the land requirement for the high-yielding intensive scenario would increase to 18.3 million hectares (S4). Furthermore, it would lead to a crucial impact on water resources because low-quality marginal land typically requires more irrigation water than already productively used land [52].

If the above presented results are compared with estimates about the current *J. curcas* plantations which range from 10.000 hectares [46] to 302.078 hectares [53], the achievement of the B20 goal in India seems in either case to be unrealistic. Moreover, considering that, as shown in [2], estimates of marginal land indicate a value of about 55 million hectares, almost all of these lands would have to be converted to *J. curcas* plantations to achieve the B20 blend in India. Since large parts of the marginal land are used for activities such as livestock grazing and gathering of wild products [4], the displacement will have direct impacts on local communities and will most likely also cause indirect land use changes. In addition, *J. curcas* plantations show less control over water, material and nutrient fluxes than wasteland and thus the land will never return to the state of natural vegetation [6].

In addition to the land use perspective, also socio-economic aspects further limit the expansion of *J. curcas* in India. Several studies proved that under the current conditions, JME production is economically not viable [5, 54].

## 5. Conclusion

This study shows that the use of JME generally reduces the global warming potential and the nonrenewable energy demand as compared to fossil fuels. On the other hand, the environmental impacts on acidification, ecotoxicity, eutrophication, and water depletion showed increases. Nevertheless, the environmental impacts of the assessed *J. curcas* value chains show large variations, which are mainly caused by the difference in crop cultivation practices and are strongly dependent on the resource efficiency during crop cultivation.

Therefore, one key aspect for achieving environmental sustainability is to increase the resource efficiency of *J. curcas* cultivation systems by enhancing the research on seed material which is optimally adapted for the local conditions and to optimize the agronomic practice. This study showed that the crop performance at the test sites is mainly determined by the water supply and the application of AM, while the yield response to the application of mineral fertilizer is marginal. Consequently, the irrigated *J. curcas* cultivation systems supplied with AM and only little fertilizer showed the highest resource efficiency and the lowest environmental impacts, except for the water depletion. It is therefore suggested, that under the same agroclimatic conditions, AM should always be applied to the crops to increase the crop performance and, if sufficient water resources are available and accessible, to adequately irrigate the crops, but only apply minimal amounts of fertilizer.

In addition, significant environmental benefits can only be achieved if *J. curcas* is cultivated on low carbon stock land. In the case study presented in this paper, *J. curcas* was cultivated on agricultural land and thus, the GWP was further reduced due to increased carbon stock. However, replacing productive land might cause indirect LUC effects, since the replaced crops are likely to be produced somewhere else. This mechanism might lead to either intensification or to expansion of productive land to natural ecosystems. Since these effects follow complex mechanisms and depend highly on local conditions, it is recommended, for planned biofuels plantations, to conduct an indepth study on the local mechanisms and to develop a land use plan including mitigation measures. This applies not only to the conversion of agricultural land, but also to marginal lands, which are often used by local communities.

Besides optimizing the cultivation system, the efficient fuel production and the optimal use of the byproducts also influence the environmental performance of *J. curcas* biodiesel. While the optimization potential of the fuel value chain is rather limited, further elaboration is particularly needed with respect to the optimal use of the press cake.

Overall, the choice of the vehicle used on Indian roads directly affects fuel consumption and thus the environmental impact caused during the fuel production. Political instruments targeting the promotion of efficient cars and providing transport alternatives (i.e, using public transport) should go hand in hand with sustainable fuel production.

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