Life Cycle Assessment of electricity generation from *Jatropha* oil in a short chain in Mali

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Abstract

Jatropha curcas is an inedible oil crop which can grow under semiarid climatic conditions. Its oil can be used straight as fuel to provide energy in remote areas to improve living conditions. The aim of this study is to assess the environmental impacts of the electricity generation from *Jatropha* oil under West African conditions, by means of a Life Cycle Assessment (LCA). These potential impacts are calculated for four crop managements and compared to the ones of a reference electricity generation from conventional diesel. Data used in this work are from *Jatropha* plantations set up in Mali since 2006.

LCA results show that the potential benefits of the *Jatropha* systems are highly dependent on the crop management, especially for the fertilization strategy and the promotion of the oilcake. However, in all cases, the *Jatropha* systems have lower impacts than the reference diesel system by 189% to 447% for climate change and by 70% to 95% for fossil resource scarcity, and higher impacts for most local and regional issues such as land use, eutrophication or acidification.

A methodological originality of this work is the inclusion of animal and human labour into the LCA framework. A first model is proposed for the accounting of energy demand and GreenHouse Gases (GHG) emissions due to labour. Concerning energy demand, labour is not negligible with a share from 13% to 50% of the total impact of the *Jatropha* systems; however the highest share of 50% corresponds to the scenarios with the lowest energy demand. CH_4 emissions from livestock are second-order in this study since they account for less than 1% of total GHG emissions.

Highlights

- An LCA on *Jatropha* production and use was performed, based on field data in Mali.
- *Jatropha* systems performed better than fossil fuel for climate change and fossil resource scarcity, but worse for most local and regional impacts.
- Fertilization strategy is a key choice for *Jatropha* sustainability.
- Animal and human labour is a second-order issue for these environmental profiles.
- *Jatropha* oilcake fate and toxicity issues are key elements for further research.

Keywords: *Jatropha curcas*; Vegetable oil; LCA; Crop management; Rural development; Remote electricity.

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Abstrak

Jarak Pagar (*Jatropha curcas*) adalah tanaman minyak yang tidak dapat dimakan yang dapat tumbuh dalam kondisi iklim semi kering. Minyaknya dapat digunakan langsung sebagai bahan bakar untuk sumber energi di daerah terpencil guna memperbaiki kondisi kehidupan. Tujuan dari studi ini adalah untuk menilai dampak lingkungan pada pembangkit listrik dari minyak jarak pagar pada kondisi Afrika Barat, menggunakan *Life Cycle Assessment (LCA).* Dampak potensial ini dihitung untuk empat pengelolaan tanaman dan dibandingkan dengan pembangkit listrik referensi dari diesel konvensional. Data yang digunakan dalam pekerjaan ini berasal dari perkebunan jarak pagar yang didirikan di Mali sejak 2006.

Hasil LCA menunjukkan bahwa potensi manfaat dari sistem jarak pagar sangat bergantung pada pengelolaan tanaman, terutama untuk strategi pemupukan dan promosi bungkil minyak. Namun, dalam semua kasus, sistem Jarak Pagar memiliki dampak yang lebih rendah daripada sistem diesel referensi sebesar 189% hingga 447% untuk perubahan iklim dan 70% hingga 95% untuk kelangkaan sumber daya fosil, dan dampak yang lebih tinggi untuk sebagian besar masalah lokal dan regional seperti penggunaan tanah, eutrofikasi atau asidifikasi.

Orisinalitas metodologis dari kajian ini adalah dimasukkannya hewan dan tenaga manusia ke dalam kerangka kerja LCA. Model pertama diusulkan untuk penghitungan permintaan energi dan emisi Gas Rumah Kaca (GRK) akibat tenaga kerja. Mengenai permintaan energi, tenaga kerja tidak dapat diabaikan dengan bagian sebesar 13% hingga 50% dari total dampak sistem Jarak Pagar; namun bagian tertinggi 50% sesuai dengan skenario dengan permintaan energi terendah. Emisi CH4 dari hewan ternak menempati urutan kedua dalam studi ini karena emisi tersebut menyumbang kurang dari 1% dari total emisi GRK.

Garis Pokok

- LCA untuk produksi dan penggunaan jarak pagar dilakukan, berdasarkan data lapangan di Mali.
- Sistem jarak pagar memiliki kinerja lebih baik daripada bahan bakar fosil untuk perubahan iklim dan kelangkaan sumber daya fosil, tetapi lebih buruk untuk sebagian besar dampak lokal dan regional.
- Strategi pemupukan adalah pilihan utama untuk keberlanjutan jarak pagar.
- Pekerja manusia dan hewan adalah masalah kedua untuk profil lingkungan ini.
- Nasib bungkil jarak pagar dan masalah toksisitas adalah elemen kunci untuk penelitian lebih lanjut.

Kata Kunci: *Jatropha curcas*; Vegetable oil; LCA; Crop management; Rural development; Remote electricity.

1. INTRODUCTION

Economic growth in developed countries, as in developing countries, is related to the increase in energy demand. On average an African consumed less energy in 2002 than an Englishman did in 1875, mainly because complete industrialization and economic modernization has yet to take place in most African countries [1]. Energy access thus contributes to the ability of a country to meet its Millennium Development Goals [2].

This has resulted in a dependence on fossil fuels, leading to the depletion of petroleum resources, the emission of GreenHouse Gases (GHG) and global warming [3] The increase and constant fluctuation in prices of oil and its environmental impacts have boosted interest in alternative and renewable energies, including biofuels. However, most first-generation biofuels are derived from food products such as maize, rapeseed or sunflower seed, giving rise to problems of competition with food for human consumption and fluctuating food prices [4][5]. This is why the interest in *Jatropha curcas* has steadily grown in recent years. This shrub of the *Euphorbiaceae* family produces inedible seeds containing 28–38% oil [6] that can be used directly as a biofuel in diesel motors. In addition, this species may be grown on marginal land under semiarid climatic conditions. It is an interesting alternative for biofuel production in the tropics and subtropics.

Few Life Cycle Assessments (LCA) have been conducted to assess the environmental impacts of cropping *Jatropha* and using its seed oil. Studies have been carried out on the production of esterified oil (biodiesel) or hydrogenated oil for use in car motors [7][8][9][10][11][12] or in trains in India [13]. All of these studies highlighted the major impact of the transesterification or hydrogenation steps. A study was conducted on straight oil production and its use in generators to enhance rural development of villages in India [14]. Results from this experience could not, however, be transposed to the West African setting due to soil and climate differences and variable growing conditions. All these studies have shown that GHG emissions and the non-renewable Cumulative Energy Demand (CED) associated with the production and use of straight or esterified *Jatropha* oil are lower than for fossil fuels, with savings between 49% and 84% for GHG emissions, and between 78% and 105% for CED.

The aim of the present study was to assess the environmental impacts of the production of straight *Jatropha* oil and its use in generators in Mali. Such use would promote rural development, reduce dependence on petroleum and sidestep the problem of its price fluctuations. It is a follow up to the study of Ndong *et al.* [8] which highlighted the impact of the transesterification and transportation steps of *Jatropha* oil, and accounted for human labour. There are three original features of this study: (1) it focused on the short chain, i.e. use of the oil where it is produced without any chemical processing, (2) it aimed to refine the modelling and recognition of both animal and human labour in LCA, while integrating energy demand and gas emission data, and (3) finally the study is based on updated field data.

2. MATERIALS AND METHODS

2.1. Goal and scope of the Life Cycle Assessment study

2.1.1. Objectives of the study

The Life Cycle Assessment (LCA) study was conducted in accordance with the principles outlined in the international ISO 14040 and ISO 14044 standards [15][16]. The LCA performed in this study was attributional, i.e. only physical life cycle flows were taken into account, regardless of potential economic or political decisions and their impacts [17].

The goal of this LCA was to compare the environmental impacts of two electricity generation systems for rural Africa involving generators: a conventional diesel fuel system, and a straight *Jatropha* oil based system, according to different crop managements.

The system was designed to supply electricity to a Malian village. The corresponding functional unit was 1 kWh of electricity produced, via a generator, from straight *Jatropha* oil or diesel fuel. Reference flows for this function corresponded to 0.28 kg of straight *Jatropha* oil or 0.27 kg of diesel [18].

2.1.2. System boundaries

The system boundaries of the LCA study accounted for the ‘cradle-to-electricity’ impacts, i.e. from the *Jatropha* nursery plants or crude oil extraction to the generation of 1 kWh of electricity to be supplied to the village, passing through all of the intermediary steps, including shrub cropping, seed transport, oil extraction and combustion of the oil in a generator (see Table 1 for *Jatropha* systems).

The *Jatropha* cropping system was modelled over the entire life cycle of this perennial crop, i.e. 30 years, in order to account for unproductive, growth and mature plant phases. The electricity required for operating the oil extraction machines was provided internally via the system by oil combustion in the generator. Impacts of the infrastructure and machinery, including processing and transportation, were considered on the basis of the amount of the main materials.

Table 1. The electricity generation process

Four phases of electricity generation from *Jatropha* oil Each step per phase is listed in chronological order			
Cropping	**Treatment**	**Extraction**	**Combustion**
Nursery Seedling transport by cart Digging planting holes Transplantation Fertilization Replacement Weeding Pruning Pest control Harvesting Tree uprooting	Fruit transport by cart Fruit pulping Storage at cooperatives Seed truck transport	Storage Cleaning Extraction Decantation Filtration	Oil combustion

Due to the low level of agricultural mechanization at Teriya Bugu, Mali, impacts on GHG emissions and energy demand from the use of livestock were assessed and taken into account. The impacts from oxen were calculated for a whole year, accounting for unproductive days, and then allocated between the different activities for which the animals were used, considering the time spent on each one. The energy supplied and methane emitted by oxen included the basal metabolism since the oxen were considered as dedicated for performing agricultural tasks.

Besides animal labour, the CED also included energy supplied by humans. Here only the surplus energy devoted to work was accounted for, since the basal metabolism should not be allocated to the LCA system.

Finally, carbon fixation by plants and CO_2 emissions during straight *Jatropha* oil combustion were not taken into account in the GHG balance. Indeed, as the carbon cycle of these latter biogenic emissions is short (1 year), their impact on global warming was disregarded.

2.1.3. Scenarios for Jatropha crop management

The study of Chaouki [19] showed the importance of fertilizers in the environmental assessments of the *Jatropha* crop. Four different fertilizing strategies for *Jatropha* crop management were then explored in this study.

Scenario A is the reference scenario. It corresponds to basic farming practices and does not take either chemical fertilizer or oilcake applications into account. Scenario B stands for what should be seen as ideal fertilizing practices: chemical fertilizers are applied during the first five unproductive years, then both *Jatropha* oilcake and complementary chemical fertilizers are applied during the next 25 years. The amount of chemical fertilizers applied is calculated based on the difference between mineral exportations due to seed harvest and mineral inputs from *Jatropha* oilcake. Scenario C is more inspired by what is actually done for cotton production; a constant amount of chemical fertilizers is applied for 30 years and oilcake is considered as a waste. Finally, Scenario D represents a situation where no money is spent by farmers on chemical fertilizers and only oilcake is applied.

These scenarios were compared to the conventional diesel fuel system, corresponding to European conditions according to *ecoinvent* v3 data for production and combustion.

2.2. Life Cycle Inventory

This LCA phase consists of quantifying all input/output flows associated with each elementary process for each step of each phase of the system [20]. This inventory was based on data from the *Jatropha* experimental station in Teriya Bugu, supplemented by literature data. The main data and hypotheses describing the *Jatropha* oil based system are outlined in the following paragraphs. Extraction and emission flows related to the production and transportation of inputs such as mineral fertilizers are from the *ecoinvent* v3 database.

2.2.1. Study site in Mali

The data used in this study were from an experimental *Jatropha* cropping station and a *Jatropha* oil production project, both of which are based in Teriya Bugu, Mali, between Ségou and Mopti, on Bani River. The geographical coordinates are 13°12’22.8” N, 5°31’35.9” W. The average rainfall in this region was 748 mm/year between 2000 and 2007 [8], concentrated mainly over a 4-month period (July-October), with some rainfall in May and June. The soils in this area are generally sandy loam or silty clay. The *Jatropha* experimental plots were initially set up in 2008 with the help of a local NGO (Mutual aid Association for Rural Development (AEDR)) in collaboration with the International Centre of Agricultural Research for Development (CIRAD) and the AgroGeneration company. The soil at the site had been cultivated for 30 years before *Jatropha* plots were set up.

AEDR, which promotes *Jatropha*, has set up some fields since 2004, and now purchases seeds from farmers to extract the oil, which in turn is used to fuel local generators as an alternative to fossil diesel.

2.2.2. Jatropha seed production

The seeds were potted and placed in nurseries to allow them to grow properly for a 2-month period before the rainy season. They were placed in polypropylene bags containing local manure (1.2% N, 0.8% P_2O_5, 1.8% K_2O). Each seedling was supplied 200 mL of water per day over the 60-day growing period in the nursery.

The soil, in which the plants were to be transplanted, required tillage using a plough pulled by oxen. This tillage aerated the soil and cleared the weeds. The plants were transported by cart from the nursery to the field and transplanted into holes dug manually just before the rainy season. During the transplantation phase, 100 g NPK (16-26-12) was applied directly into each hole to prevent nutrient leaching by rain. The planting density was 1,250 plants/ha. 1500 plants were required to offset the 10% losses that generally occur during the transplantation phase.

The field was manually weeded during the rainy season twice per year during the first 3 crop years and once per year thereafter. Traditionally farmers do not fertilize this crop, at most they can apply the oilcake[2]. However, some farmers were willing to apply a small amount of chemical fertilizer (125 kg of NPK 16-26-12). Potential fertilization strategies explored in this study are given in Table 2. For Scenario B, mineral needs of the crop after applying oilcake were calculated and it was found that 100 kg/ha/year of KNO_3, 13% N and 44% K, were needed.

The shrubs were pruned with a machete as of the second year to increase flowering and thus ensure a good seed yield. Harvesting was done manually from August to December. Termite attacks on *Jatropha* crops were increasingly frequent, so chemical control treatments were necessary during the first 5 years (5 kg/ha of Carbofuran each year).

Yields increased until the fifth or sixth crop year and then stabilised during subsequent years. A worker harvested 52 kg of fruit, or 30 kg of dry seeds per day on average, with 30% oil content.

Productivity curves according to applied fertilizer dosages were required in order to compare the different scenarios given in Table 2. Realistic data, representative of rural areas and West African conditions, were then needed. Extensive research has been conducted on Brazilian data [21][22]. However, few references were found on conditions similar to those that prevailed in the present study. It was therefore necessary to estimate productivity curves on the basis of the first results obtained on experimental plots and on the production data recorded at Teriya Bugu.

The *Jatropha* experimental plots provided data for the first three years in Scenarios A and C. The fields cropped by AEDR also contributed in Scenario A description for the first six years. These available data were then completed through the experience of the local manager in Mali and of a researcher from CIRAD. Predictive models were not used to obtain productivities of *Jatropha* seeds. Indeed existing models assume ideal conditions of irrigation and crop management which are unrealistic for this study. Estimated scenarios of *Jatropha* seed yields, based on existing data from Teriya Bugu and Brazil [22], are given in Fig. 1 and Table 3.

Table 2. Fertilization rates of Scenarios B, C and D

Scenario	Chemical fertilizer	Oilcake	Comments
A			No fertilizer
B	X	X	Chemical NPK fertilizer (125 kg/ha/year, 16-26-12) applied for the first 5 years, and chemical KNO_3 fertilizer (100 kg/ha/year, 13% N, 44% K) applied for the next 25 years Oilcake applied for 30 years
C	X		Chemical NPK fertilizer (125 kg/ha/year, 16-26-12) applied for 30 years
D		X	Oilcake applied for 30 years

[2] It must be noted that the non-toxicity of using oilcake as a fertilizer has not been demonstrated at the moment.

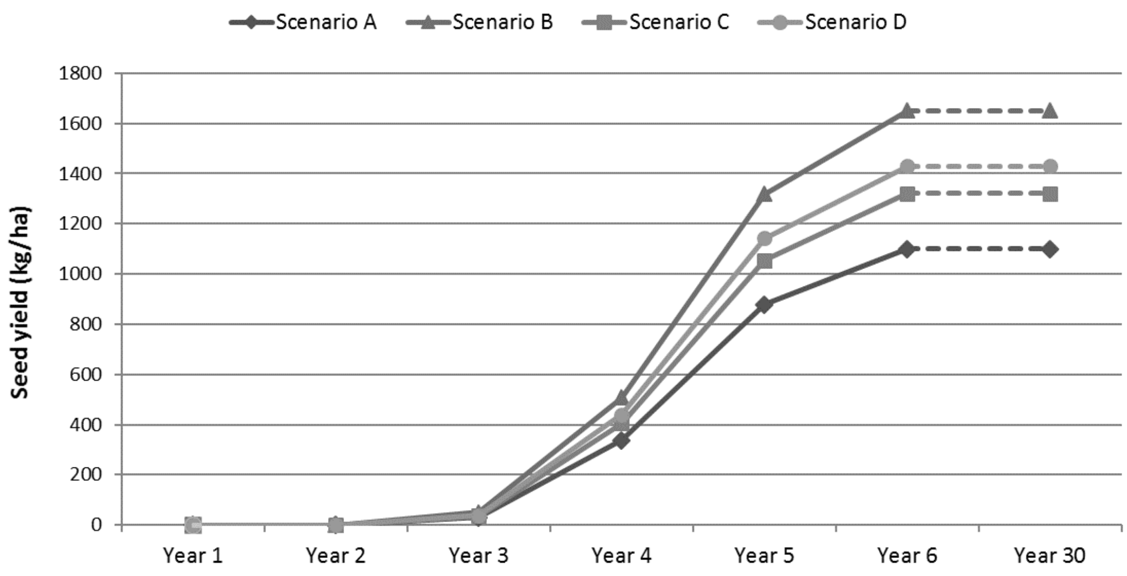

Fig. 1. Estimations of seed productivities of *Jatropha* crop scenarios

Table 3. Yields (kg/ha) obtained yearly under the different scenarios

Scenario	**Year 3**	**Year 4**	**Year 5**	**25 years plateau**	**Yield estimated according to scenario A**
A	30	338	879	1100	100%
B	50	507	1318	1650	150%
C	36	406	1055	1320	120%
D	39	439	1143	1430	130%

2.2.3. Field emissions

Application of chemical fertilizer (in the form of NPK fertilizer or potassium nitrate) and organic fertilizer (oilcake) leads to pollutant emissions into the environment. The inventory included direct and indirect emissions of N_2O, NH_3 and NO into air, as well as NO_3 and phosphorus into water. All hypotheses required for calculating these emissions are from the studies of EEA [23], de Klein *et al.* [24] and Nemecek & Schnetzer [25], and are summarized in Tables 4–6. Emission rates were calculated in relation to the amounts of nitrogen and phosphorus available in the chemical or organic fertilizer.

Table 4. Direct NH_3, N_2O, NO and NO_3 emissions

Substance	*Product*	*Compartment*	*Rate*	*Source*
NH_3-N	*Both*	*Air*	*3.05%**	EEA, Tier 2 [23]
N_2O-N	*Both*	*Air*	*1%*	de Klein *et al.*[24]
NO-N	*Both*	*Air*	*1.2%*	EEA, Tier 1 [23]
NO_3-N	*Both*	*Water*	*30%*	de Klein *et al.* [24]

* This emission factor was provided by EEA [23], Tier 2 methodology, based on the “Other NK and NPK” type for all chemical fertilizers and oilcake.

Table 5. Indirect N_2O emissions

Substance	*Product*	*Compartment*	*Rate*	*Source*
N_2O-N (from volatilization)	*Chemical*	*Air*	*0.043%*	de Klein *et al.* [24]
	Organic		*0.085%*	
N_2O-N (from leaching / run-off)	*Both*	*Air*	*0.225%*	de Klein *et al.* [24]

Table 6. Phosphorus emissions to water

Substance	*Product*	*Compartment*	*Rate*	*Source*
P (from run-off)	*Chemical* *Organic*	*Water*	*0.1%** *0.2%**	Nemecek & Schnetzer [25]

* These emission factors were provided by Nemecek & Schnetzer [25], based on the "Mineral fertiliser" type for chemical fertilizer and the "Solid manure" type for organic fertilizer.

Table 7. Estimation of aboveground and soil organic carbon stocks for the different considered systems, according to IPCC 2006, Tier 1 methodology

Systems	*Native stock (tC/ha)*	*Land Use Factor*	*Land Management Factor*	*Input Level*	*Total SOC stock (tC/ha)*	*Aboveground carbon stock (tC/ha)*	*Total stock (tC/ha)*
Previous land use	*33**	*0.58*	*1.09*	*0.95*	*19.8*	*0*	*19.8*
Jatropha, Scenario A	*33**	*1*	*1.09*	*0.95*	*34.2*	*9*	*43.2*
Jatropha, Scenario B	*33**	*1*	*1.09*	*1.37*	*49.3*	*9*	*58.3*
Jatropha, Scenario C	*33**	*1*	*1.09*	*1.04*	*37.4*	*9*	*46.4*
Jatropha, Scenario D	*33**	*1*	*1.09*	*1.37*	*49.3*	*9*	*58.3*

* This native SOC stock value was estimated as the average of the values for sandy soils (35 tC/ha) and low activity clay soils (31 tC/ha) in tropical dry climate.

Changes in aboveground biomass and Soil Organic Carbon (SOC) were accounted for based on IPCC Tier 1 methodology (Table 7)[26]. According to the study site description (see section 2.2.1) and IPCC guidelines, local conditions were classified as tropical dry climate and both sandy and low activity clay soils. The previous land use was considered as long-term cultivated and the *Jatropha* cropping systems as perennial crop. Management factors are detailed in the following Table 7, along with carbon stock results. The differences in carbon stocks between the previous land use and the different *Jatropha* systems were allocated over the whole perennial crop cycle.

2.2.4. Jatropha oil production and use

After harvest, *Jatropha* fruits were dried under natural ambient conditions and transported by cart pulled by oxen to a shed at the cooperative where they were hulled using a manual huller. The seeds were then trucked to the oil extraction centre, where the seeds were cleaned mechanically with a winnower and then cold pressed to extract the oil. The 7.5 kVA press had an extraction efficiency of 76%. After a settling phase in drums, the oil was filtered mechanically through a 1-µm filter in order to remove extraction residues. The oil could thus be stored or used directly to fuel a 20 kVA generator.

Fig. 2 shows the products and by-products obtained during the biofuel production process. The oilcake, for example, can be used as organic fertilizer (scenarios B and D) or disposed as waste (scenarios A and C). The oil is often traditionally used for making soap, but also used in small quantities as a medicine. However, all of the oil produced in this study was used as biofuel in a generator. Combustion yield for *Jatropha* oil considered in this study was 0.28 kg oil/kWh electricity [18]. Table 8 specifies the associated emissions. Emissions from diesel combustion in the diesel system were reported according to the *ecoinvent* v3 database.

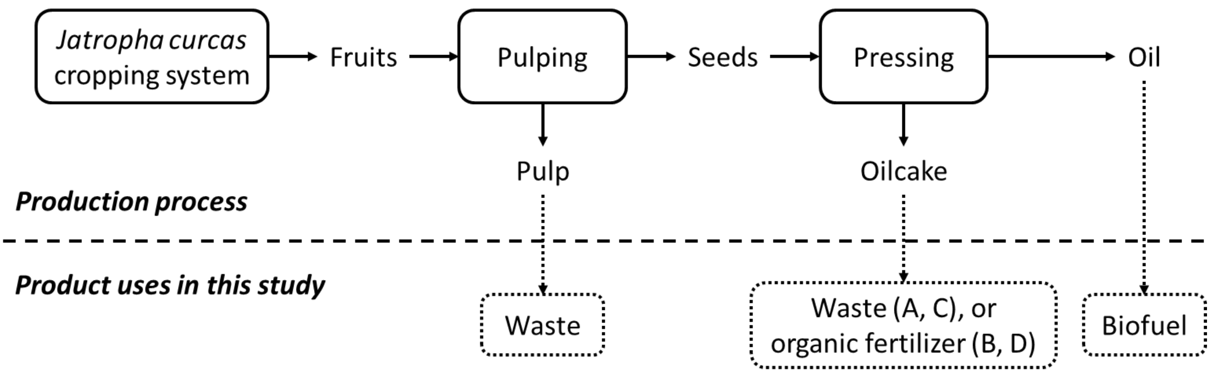

Fig. 2. *Jatropha curcas* products and their uses considered in this study

Table 8. Emissions from *Jatropha* oil combustion [18]

	CO_2	*CO*	*NOx*	*HC*
Emissions (g / kWh)	-	2.00	2.91	0.722

2.2.5. GHG emissions and energy demand from animal and human labour

Jatropha production should be seen as labour-intensive: oxen are used for tillage and seed transportation from fields, and human labour takes part in many agricultural activities. Considering labour as a free resource was then seen as a potential bias and so animal and human labour was accounted for in this study. An underlying objective was to determine the potential impact of such an assumption in final LCA results.

As a first approximation, life cycle impacts of food and feed production were not taken into account and only metabolic energy demand and associated GHG emissions were considered. Oxen were assumed to be dedicated to labour, therefore full metabolism was included. Furthermore, oxen were supposed to work three months each year, then three non-working days were allocated to each working day. For human labour, only extra metabolism due to agricultural activities related to the *Jatropha* crop was included.

Table 9 pools the different energy needs of a pair of oxen (total weight of 350 kg). Basal metabolism of livestock was provided by grass, with an energy content of 0.5 Feed Units for Lactation (FUL) per kg and an assimilation rate by oxen of 65%. The energy required for extra effort due to labour was obtained from cotton oilcake with an energy content of 0.8 FUL per kg and an assimilation rate of 80%.

Emissions of CH_4 associated to livestock metabolism were calculated from the dry mass of ingested feed, the carbon content of ingested feed and the conversion rate of ingested carbon into CH_4. The carbon content of savannah grass and cotton oilcake was 40% of the dry mass, and the conversion rate into CH_4 was 3.8% [28]. Associated biogenic CO_2 emissions were not accounted for in the impact assessment.

Finally, human energy was calculated on the basis of an extra metabolism due to agricultural activities of 73.6 W [29].

2.2.6. Modelling the end of life of Jatropha oilcake

According to the considered crop scenarios, two fates were possible for the *Jatropha* oilcake produced during the oil extraction: use as an organic amendment in *Jatropha* crop fields, or discarding it on a waste pile. The effects of using this oilcake as organic fertilizer were described in the previous paragraphs.

Concerning discarding the oilcake as a waste, given the lack of data on its degradation and as a first approximation, the same emission coefficients as applied when this oilcake is used as fertilizer were considered (for N_2O, NO and NH_3 emissions to air, and NO_3 and P emissions to water). In addition, fermentation of this organic matter was considered in the form of an additional CH_4 emission. The CH_4 emission rate related to oilcake degradation was very uncertain because there is currently no reliable experimental measurements on this decomposition under tropical climatic conditions, and secondly because it is unlikely that this cake would be left as waste without being utilized for decades. Thus, rather than adopting an emission rate related to total decomposition of the cake, which could reach values of around 300 g of CH_4 per kg of oilcake according to the data reported by Nielsen & Hauschild [30][31], an emission rate matching that related to composting was used. Data related to composting waste from palm oil mills in Malaysia was chosen because of the similar tropical conditions [32][33]. Thus an emission rate of 29.7 g of CH_4 per kg of oilcake was calculated.

These impacts of the discarded oilcake were attributed to the life cycle stage of oil extraction.

Table 9. Energy demand of oxen

Activity	*Energy demand* FUL	kWh	*Source*
Basal metabolism (daily)	*3.85*	*7.8*(1)	CIRAD [27]
Working day metabolism (daily)	*5.25*	*10.7*(1)	CIRAD [27]
Extra metabolism due to labour (daily)	*1.4*	*2.8*(1)	Calculated
Transport of 300 kg for 1 km	*0.14*	*0.28*(1)	Calculated(2)

(1) Feed Unit for Lactation (FUL): 1 FUL = 2.03 kWh

(2) Based on the assumption of equivalency between extra metabolism due to labour and extra metabolism due to transportation of a cart (600 kg at full load) for 10 km (4 hours at 2.5 km h^{-1})

2.3. *Life Cycle Impact Assessment*

The impact assessment calculations were performed using SimaPro 9.0 software. The main impact assessment method used was ReCiPe 2016 Midpoint, Hierarchist version. An indicator of non-renewable Cumulative Energy Demand (CED) was also considered, including non-renewable along with livestock and human energy. For interpretation, note that this indicator is extensively redundant with the fossil resource scarcity indicator from ReCiPe, but it allows investigating the contribution of livestock and human energy to the energy demand.

Toxicity and ecotoxicity indicators were not taken into account due to the uncertainties on the impact of toxic compounds under tropical conditions and the lack of specific data on the contamination of soil, groundwater or food crops by toxic substances in *Jatropha* oilcake.

3. RESULTS

The life cycle impact results for the four *Jatropha* scenarios and the conventional diesel fuel for generating 1 kWh of electricity are shown in Fig. 3. In the subsequent paragraphs, contributions to impacts of the life cycle stages of the *Jatropha* systems are presented for the following impact categories: climate change, fossil resource scarcity and CED, terrestrial acidification, freshwater and marine eutrophication, and ozone formation. Contributions to the other impact indicators are given in Supplementary Information.

3.1. Climate change

The GHG balances of the studied scenarios are shown in Fig. 4. All *Jatropha* scenarios resulted in a net benefit for climate change mitigation. GHG emission reductions compared to the conventional diesel fuel system ranged from 189% for scenario C to 447% for scenario D. These results were mainly due to *Jatropha* cultivation, and more specifically to the increase in aboveground biomass and soil organic carbon stocks due to the establishment of a perennial cropping system.

Among *Jatropha* systems, scenarios B and D had the greatest benefits because of their high carbon stock, partly explained by the use of the oilcake as organic amendment. In contrast, scenarios A and C had the lowest benefits due to the combination of a lower carbon stock and an additional impact from discarding the oilcake, attributed to oil extraction in Fig. 4. In scenarios B and D, oil extraction showed negative results because of the self-consumption of electricity; this effect was fully compensated by the oilcake degradation in scenarios A and C.

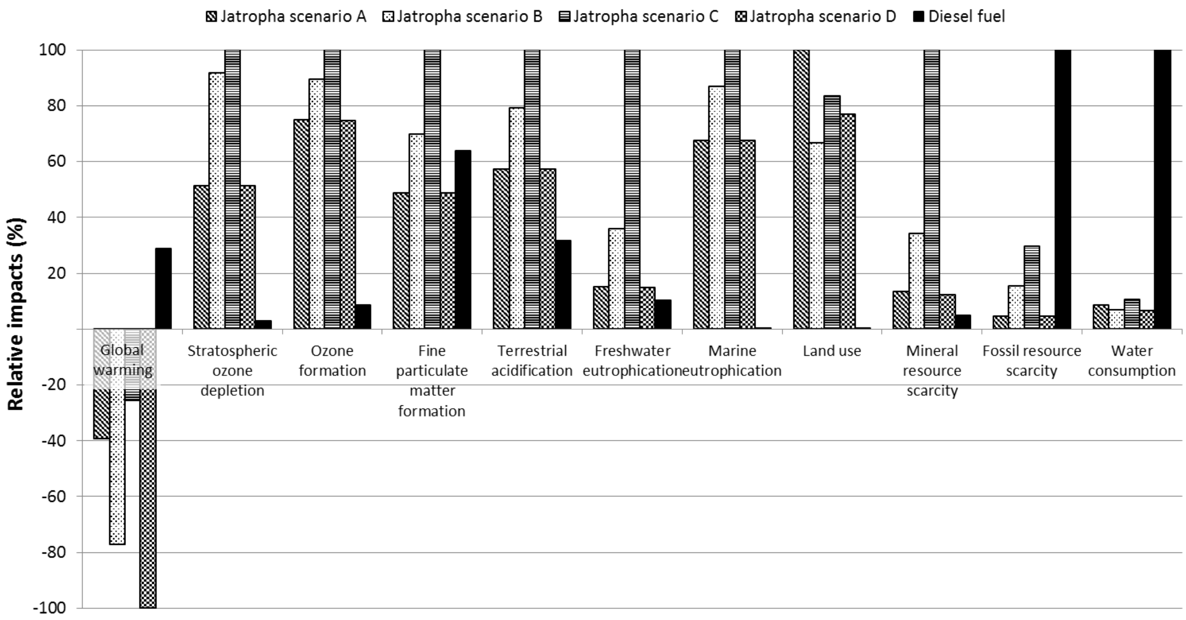

Fig. 3. Life Cycle Impact Assessment results (ReCiPe 2016, Hierarchist) of the generation of 1 kWh of electricity from the four *Jatropha* scenarios and conventional diesel fuel

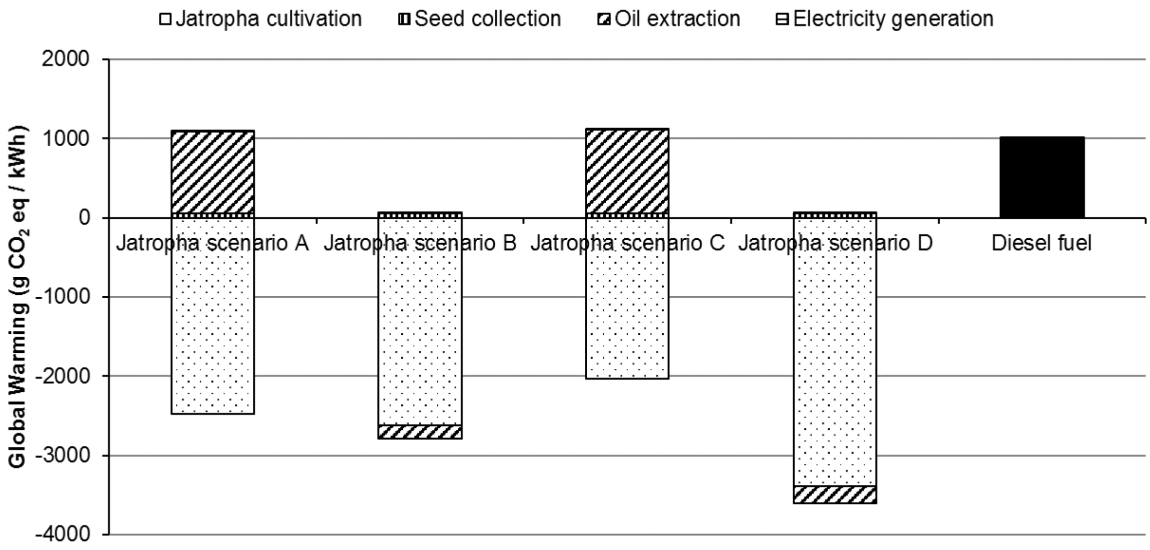

Fig. 4. Life cycle GHG emissions of the studied scenarios

3.2. Fossil resource scarcity and CED

Results for the fossil resource scarcity indicator are given in Fig. 5. Regardless of the scenario, for this impact the *Jatropha* scenario results were well below those of the conventional diesel fuel system, with reductions of 70-95%. For scenarios B and C in which chemical fertilizers were used, fertilizers were the main contributors to resource scarcity, with a total of 70% and 85%, respectively. Concerning scenarios A and D, the main contributor was motor lubricating oil, representing 32% and 33% of the impacts in this category.

The non-renewable primary CED calculation for each chain was added to this fossil resource scarcity assessment. The main advantage of using this indicator in this particular study was to enable a comparison of the use of fossil energy to the livestock and human energy. The results are shown in Fig. 6. The trends shown in Fig. 6 are essentially the same as those in Fig. 5: the *Jatropha* scenarios had CED 66–91% lower than that of the conventional diesel fuel system. CED in scenarios B and C was dominated 54% and 74%, respectively, by chemical fertilizer production.

Scenarios A and D, which had the lowest energy demands in absolute terms, were the most affected by the integration of animal and human energy. Manual pulping of seeds in their case was the most important energy demand, representing 23% of total demand of scenario A and 24% of scenario D.

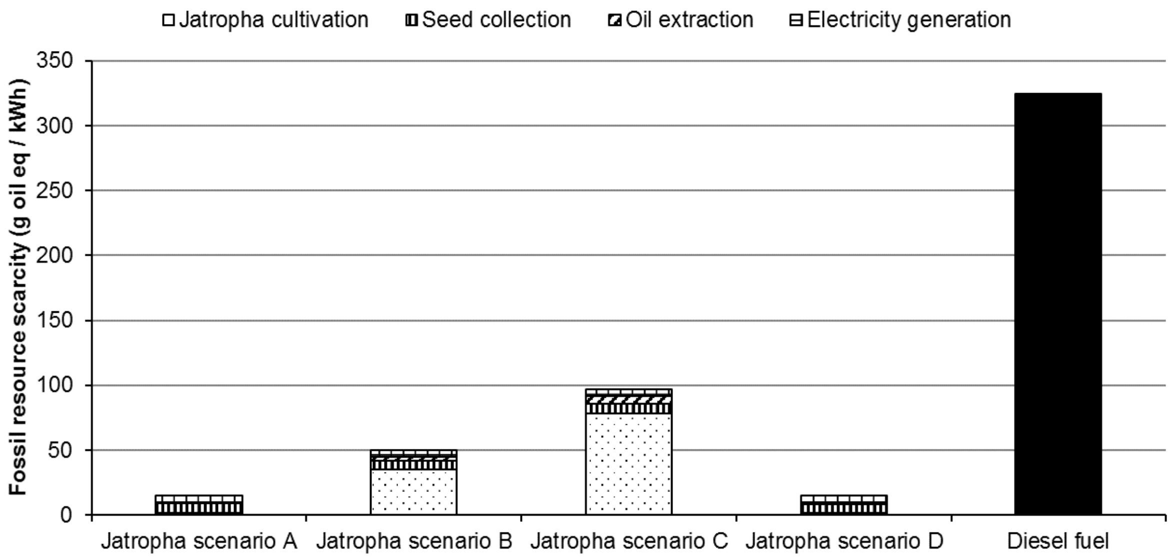

Fig. 5. – Fossil resource scarcity of the studied scenarios

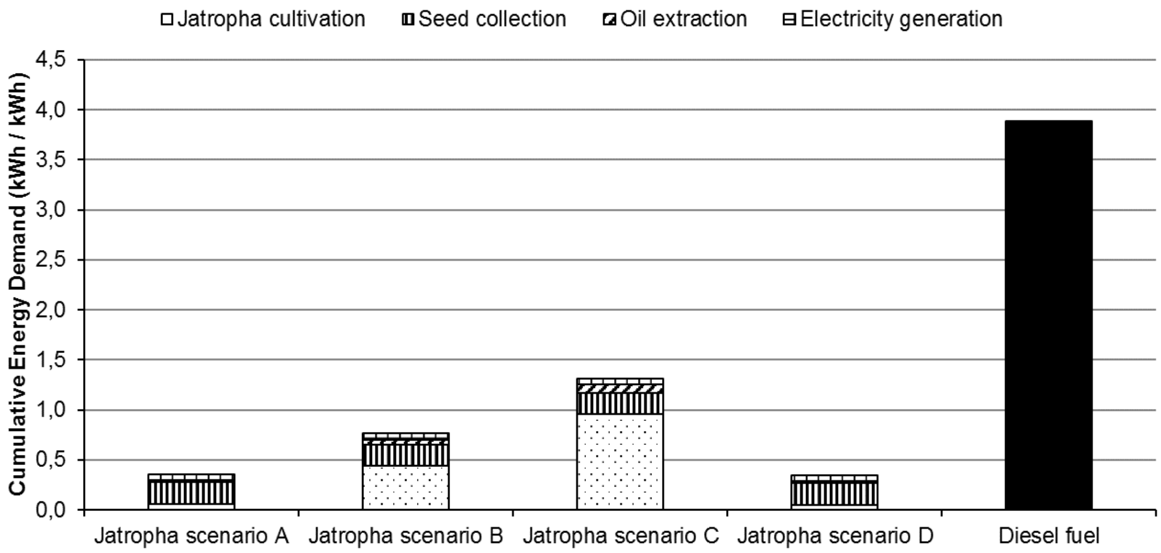

Fig. 6. CED of the studied scenarios

3.3. *Terrestrial acidification*

The results of this study on terrestrial acidification impacts are given in Fig. 7. The results in this Figure show that all of the *Jatropha* scenarios considered had a greater impact than the conventional diesel fuel system. Their emissions were mainly related, by 64% to 82% depending on the scenario, to the nitrogen input, during the chemical fertilizer manufacturing process or the application of these organic or chemical fertilizers, or otherwise to the assumed degradation of oilcake when not recovered.

The second emission source concerned NOx formation during oil combustion. Its contribution ranged from 13% to 23% depending on the scenario. However, in absolute terms, this combustion generated fewer impacts than NOx and SO_2 emissions associated with diesel combustion.

3.4. *Freshwater and marine eutrophication*

Results for freshwater and marine eutrophication are shown respectively in Fig. 8 and 9. All of the *Jatropha* scenarios studied here had a greater freshwater and marine eutrophication potentials than that of the conventional diesel fuel system, even if this trend is more pronounced for marine eutrophication than for freshwater eutrophication.

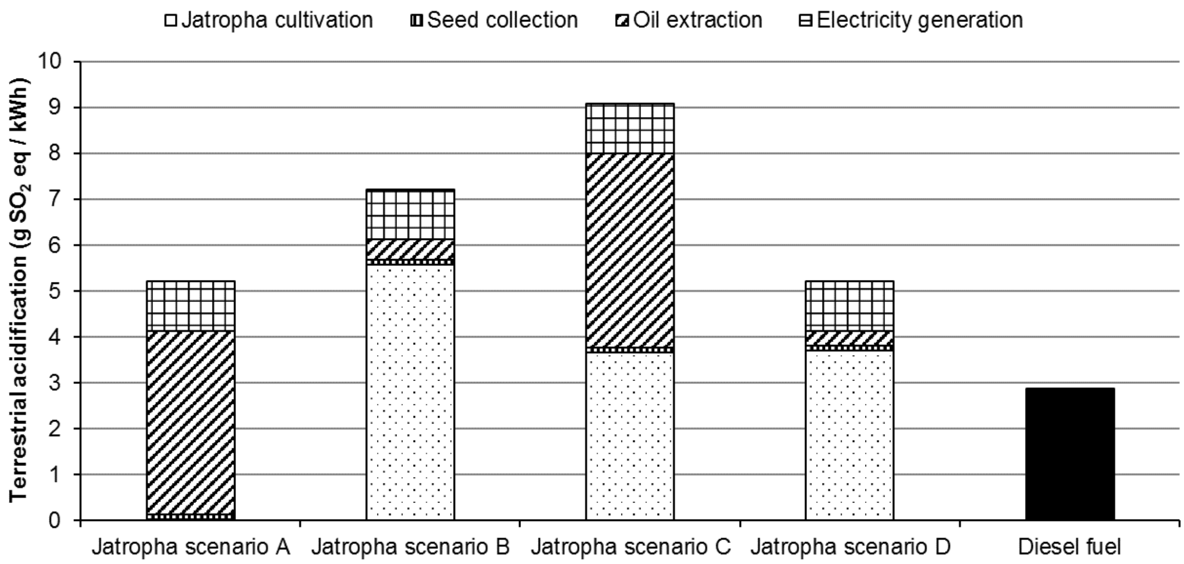

Fig. 7. Acidification potential of the studied scenarios

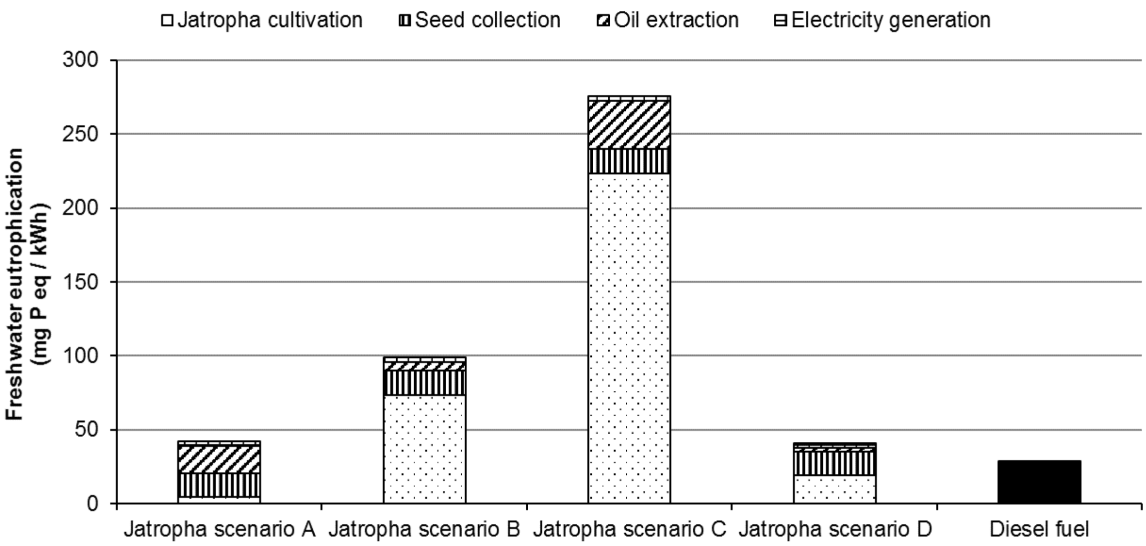

Fig. 8. Freshwater eutrophication potential of the studied scenarios

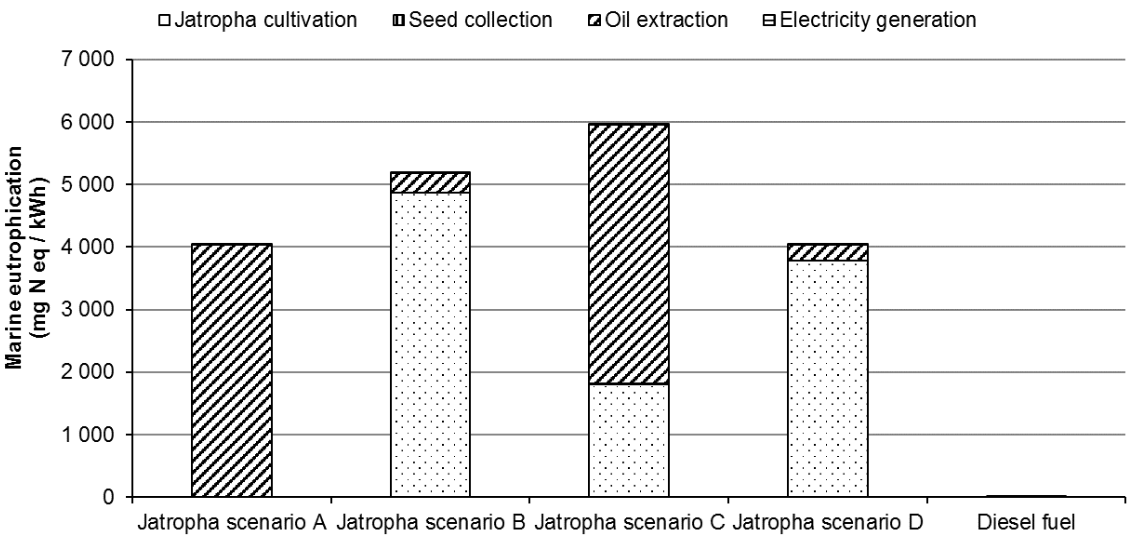

Fig. 9. Marine eutrophication potential of the studied scenarios

The impacts of *Jatropha* systems were mainly explained by the fate of phosphorus and nitrogen compounds from fertilizers and oilcake, and by the production of fertilizers. Scenarios A and D, which did not use chemical inputs, performed better than scenarios B and C for both indicators. This effect was found to be more important in the case of freshwater eutrophication, for which the role of chemical fertilizers was more important than that of oilcake. In this case, 83-86% of the impacts related to chemical fertilizers were due to their production. Conversely, impacts of the *Jatropha* systems on marine eutrophication were mostly due to field emissions.

In comparison with the acidification impact category, oil combustion had a more limited role for eutrophication, representing only 1% to 7% of the freshwater eutrophication impacts and 0% of the marine eutrophication impacts.

3.5. Ozone formation

The results for ozone formation are given in Fig. 10. All *Jatropha* systems had greater impacts than that of the conventional diesel fuel system. These impacts came from NOx emissions arising from field emissions, oil combustion, and oilcake degradation in the cases of scenarios A and C. For all scenarios, oil combustion was the main contributor to ozone formation, representing 44% to 59% of the impacts.

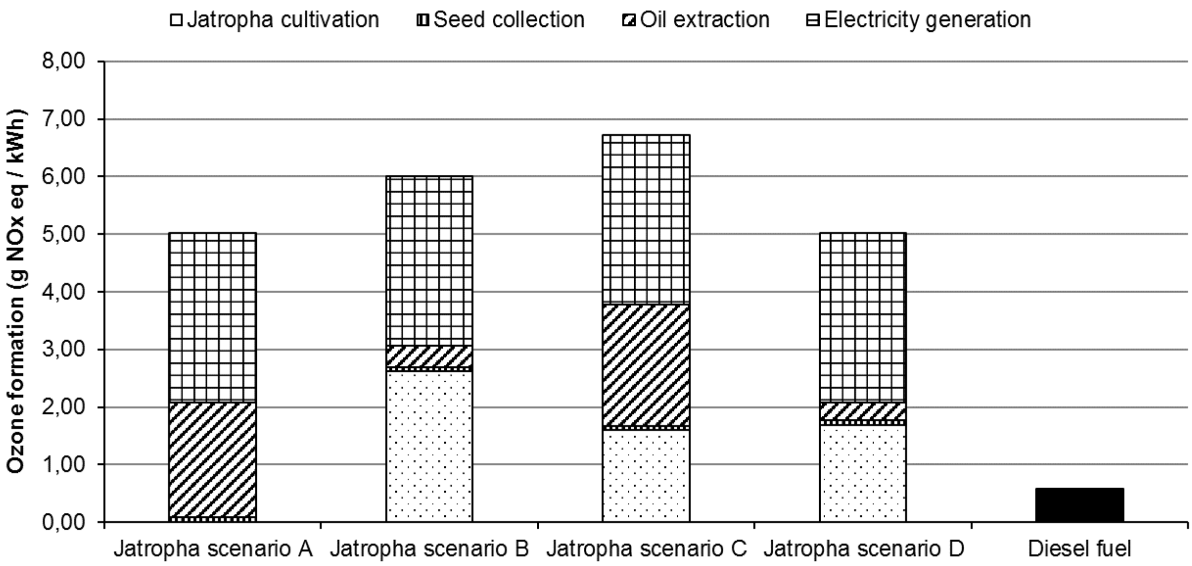

Fig. 10. Ozone formation potential of the studied scenarios

4. DISCUSSION AND CONCLUSIONS

4.1. Comparison of crop management strategies for Jatropha *seed production*

Beyond the comparison of *Jatropha* oil and diesel fuel systems for electricity generation in rural Africa, this study also assessed the performance of *Jatropha* seed production using different crop management strategies. The LCA approach enabled to compare the impacts associated with the use of agricultural inputs with the benefits gained in terms of increased yield.

Yield differences between the scenarios were minor, due to the marginal climatic conditions for *Jatropha* cropping in the study area. Hence, the response to mineral fertilization was generally moderate since rainfall was the main limiting factor. The organic matter contribution from oilcake enhanced the value of the mineral supplement provided in scenario B.

From a purely agricultural standpoint, and since tropical soils have low and regularly decreasing organic matter content, it could be argued that B and D are the scenarios that best protect the farmers' land assets because they improve soils through the use of oilcake as organic fertilizer, increasing soil organic matter. The *Jatropha* crop could thus be seen as a rehabilitation fallow. Although this aspect was considered in this study through IPCC estimations of carbon stocks, long-term experiments are required to confirm it and to enhance stock estimates.

This observation increases the extent of the finding related to the impact of oilcake degradation when this product is discarded as a waste (scenarios A and C), which is actually a credible alternative. Other types of recovery (anaerobic digestion, combustion, etc.) should have been comparatively assessed, but they were not the focus of the present study.

The above findings apply only to the agricultural aspect relative to the environmental aspect. Social and economic aspects should also be taken into account to help determine the best crop management strategy.

4.2. Relevance of decentralized rural electricity generation from Jatropha *oil in comparison to conventional diesel fuel*

Table 10 provides an overview of the advantages and disadvantages of all *Jatropha* systems compared to fossil diesel fuel.

The *Jatropha* scenarios systematically had lower impacts than diesel fuel for climate change, fossil resource scarcity, and water consumption. In contrast, these systems had adverse impacts with respect to stratospheric ozone depletion, ozone formation, terrestrial acidification, freshwater and marine eutrophication, land use and mineral resource scarcity. These trends are quite common for LCA of biofuels from energy crops [34]. Only fine particulate matter formation showed more mixed results, with conclusions depending on the *Jatropha* scenario considered.

Table 10. Benefits and shortcomings of the *Jatropha* scenarios compared to conventional diesel fuel

	Scenario A	Scenario B	Scenario C	Scenario D
Climate change	++	++	++	++
Stratospheric ozone depletion	--	--	--	--
Ozone formation	--	--	--	--
Fine particulate matter formation	+	=	--	+
Terrestrial acidification	--	--	--	--
Freshwater eutrophication	-	--	--	-
Marine eutrophication	--	--	--	--
Land use	--	--	--	--
Mineral resource scarcity	--	--	--	--
Fossil resource scarcity and CED	++	++	++	++
Water consumption	++	++	++	++

+ : Superior performance of the *Jatropha* system
- : Inferior performance of the *Jatropha* system
++ / -- : Over 50% difference
= : Similar performance (difference lower than 10%)

Independently of the crop management strategies, promoting biofuels from *Jatropha curcas* instead of fossil fuels involves a common biofuel compromise, with clear benefits for climate change, fossil resource scarcity, and, in this case, water consumption, along with increased impacts for land use, acidification, eutrophication, ozone layer depletion, and ozone formation. If local communities accept this compromise, scenario D should then be recommended since this scenario maximizes benefits on climate change and fossil resource scarcity, while minimizing the additional impacts on local and regional impacts.

4.3. *Accounting for animal and human labour*

One of the originalities of this study was the integration in the *Jatropha* scenarios of animal and human labour as energy demands and, with respect to livestock, as a source of GHG emissions. Beyond the methodological considerations, this topic is very controversial because of the strong social and ethical components. Here these impacts were considered in order to monitor their effects on the results in practice, while also not distracting attention from the labour necessary for agricultural production in these systems because of the low mechanized farming rates in this part of Africa.

The results showed that, under the hypotheses put forward to account for these energies, their effects on CED were noteworthy but relatively minor. In absolute terms, animal and human labour represented an energy demand of 0.17-0.18 kWh / kWh of electricity produced, including 0.09 kWh / kWh for manual pulping of *Jatropha* fruits. This represented 13–50% of the final CED, with this latter value corresponding to scenarios A and D for which the final CED was very low relative to that of diesel. So in the context of this study, energy demand associated with animal and human labour only became truly significant when the CED were very small.

The situation was similar for GHG emissions since absolute CH_4 emissions from livestock represented 0.04 kg CO_2 eq / kWh, i.e. less than 1% of the results across all scenarios. These emissions were then second-order in this study.

Thus, even if the inclusion of labour in LCA can be improved from a methodological perspective, results of this study tend to show that the environmental impacts of labour in African countries such as Mali are low compared to other energy demands or GHG emission sources. Priorities in terms of methodological improvement should then be placed on the combination of the environmental and socio-economic perspectives on this issue, along with refining the implications of labour in terms of health and food demands.

4.4. *Conclusions: Perspectives for* **Jatropha** *cropping systems in Africa*

Using *Jatropha* oil as a substitute for diesel for the purpose of decentralized electricity production in Mali is an issue that should be considered from many angles: agricultural, economic, social and environmental. The present study focused on the latter. However, data availability is limited and data from projects that had been set up for some years had to be retrieved to obtain objective results. Data were thus obtained from Malian plots that had been studied for 6 years, along with Brazilian data in similar pedoclimatic conditions. The findings should then be relatively representative.

While environmental criteria are not a priority for smallholders in their crop management choices, the present study aimed at highlighting this aspect. It showed that systems managed with low chemical inputs and oilcake recovery (systems similar to those used by farmers) are the most effective from an environmental standpoint. When compared to fossil fuel, biofuels from *Jatropha* present results similar to tendencies from the literature, with benefits for climate change and fossil resource scarcity but higher impacts for local and regional impact categories. However, *Jatropha* systems show specific benefits on carbon stocks due to perennial cropping and to oilcake use as an organic amendment. These aspects should then be investigated further with long-term experiments to estimate potential carbon stocks under different *Jatropha* crop management strategies.

In this study, a toxicity assessment of *Jatropha* systems is lacking since only few data are available on the effect of toxic chemicals contained in oilcake. Moreover, little is known about the fate of these products, especially with respect to the share that is potentially leached into streams and groundwater, and the share destroyed by the soil flora and fauna.

Finally, farmers' adoption of the *Jatropha* innovation has given rise to new cropping methods in the area. The limited availability of land, and the fact that certain social categories cannot set up field plantations, has prompted farmers to favour mixed *Jatropha*-annual crop systems, with the *Jatropha* crop planted in strips or hedges. It would be interesting to study this trend from an environmental standpoint, for different mixed systems. In these systems, fertilizer inputs could be used by all crops which, in addition to the agricultural and economic benefits, should increase uptake efficiencies and reduce the impact on the environment.

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Supplementary Information

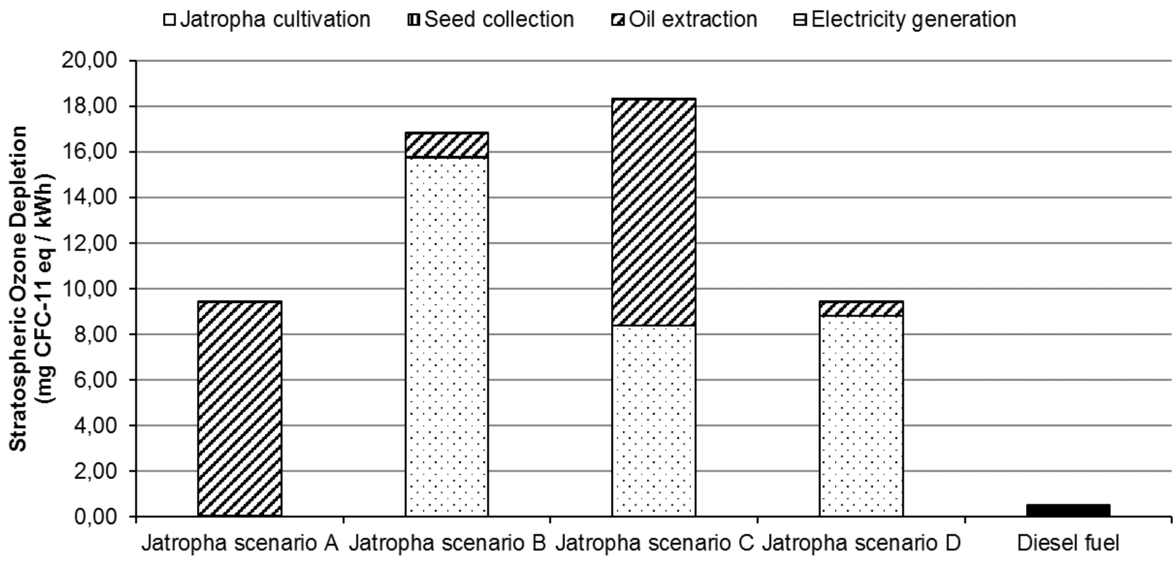

Fig. S1. Stratospheric ozone depletion potential of the studied scenarios

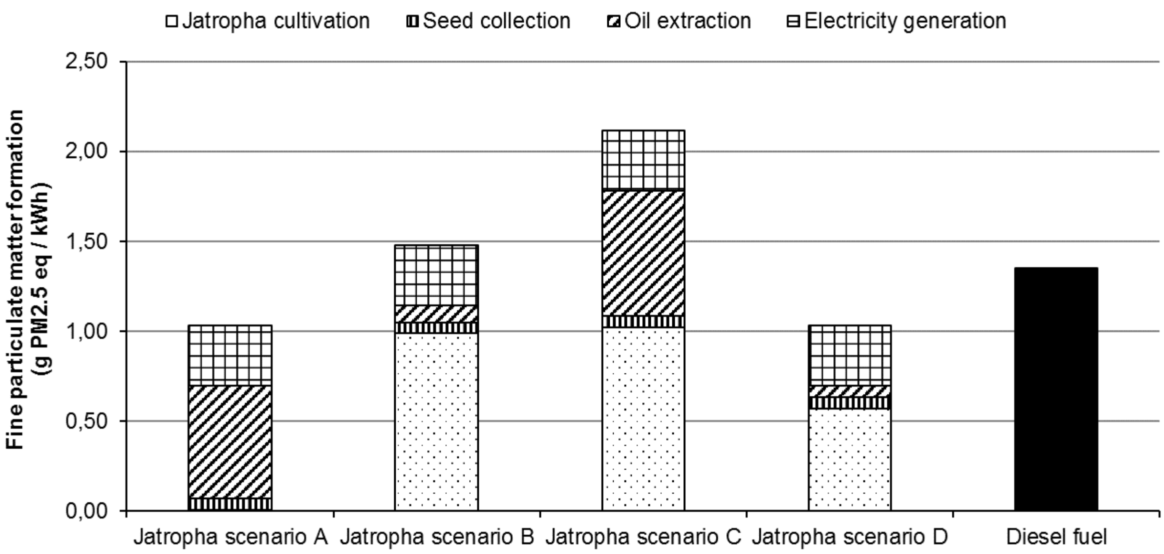

Fig. S2. Fine particulate matter formation potential of the studied scenarios

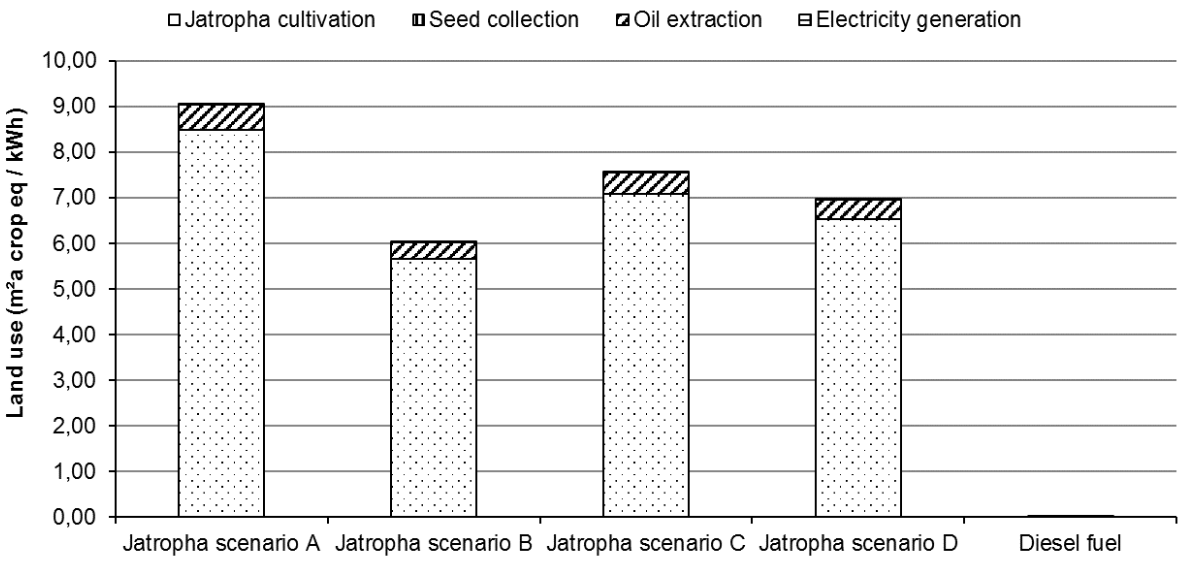

Fig. S3. Land use of the studied scenarios

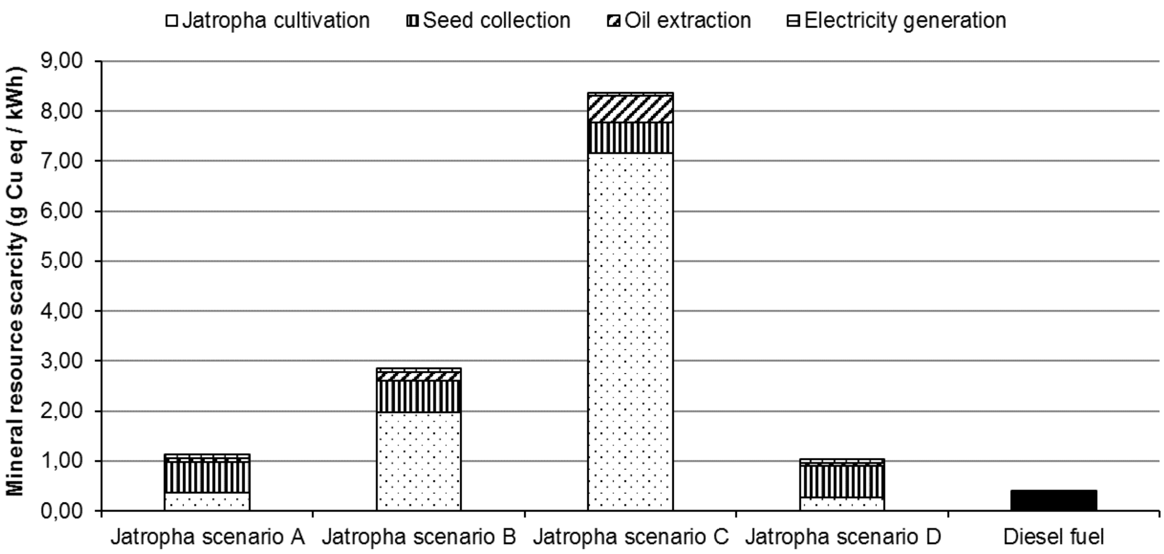

Fig. S4. Mineral resource scarcity potential of the studied scenarios

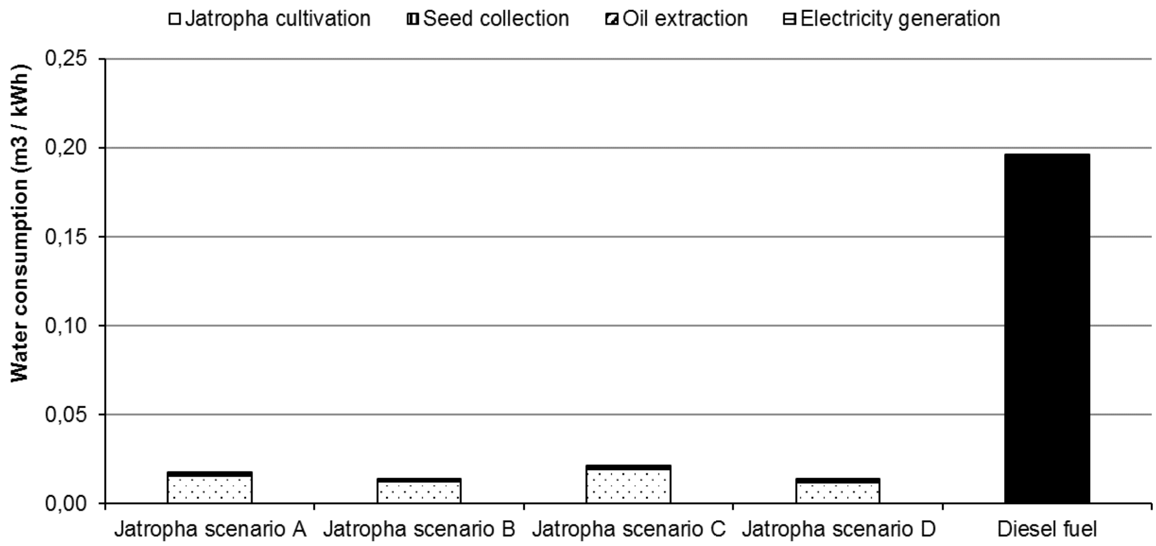

Fig. S5. Ozone formation potential of the studied scenarios