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Authors: W.M.J. Achten[a], L. Verchot[b], Y.J. Franken[c], E. Mathijs[d], V.P. Singh[e], R. Aerts[a] and B. Muys[a, *]

[a] Katholieke Universiteit Leuven, Division Forest, Nature and Landscape, Celestijnenlaan 200 E Box 2411, BE-3001 Leuven, Belgium

[b] World Agroforestry Centre (ICRAF) Head Quarters , United Nations Avenue, P.O. Box 30677, Nairobi, Kenya

[c] FACT Foundation, Horsten 1, 5612 AX Eindhoven, The Netherlands

[d] Katholieke Universiteit Leuven, Division Agricultural and Food Economics, Willem de Croylaan 42 Box 2424, BE- 3001 Leuven, Belgium

[e] World Agroforestry Centre (ICRAF) Regional office for South Asia, CG Block, 1st Floor, National Agricultural Science Centre, Dev Prakash Shastri Marg, Pusa, New Delhi - 110 012, India

* Corresponding author. Tel.: +32 (0) 16 329726; Fax: +32 (0) 16 329760; *E-mail address*: bart.muys@biw.kuleuven.be (B. Muys)

Title

Jatropha bio-diesel production and use

Authors

W.M.J. Achten[a], L. Verchot[b], Y.J. Franken[c], E. Mathijs[d], V.P. Singh[e], R. Aerts[a] and B. Muys[a, *]

Affiliations

[a] Katholieke Universiteit Leuven, Division Forest, Nature and Landscape, Celestijnenlaan 200 E Box 2411, BE-3001 Leuven, Belgium
[b] World Agroforestry Centre (ICRAF) Head Quarters, United Nations Avenue, P.O. Box 30677, Nairobi, Kenya
[c] FACT Foundation, Horsten 1, 5612 AX Eindhoven, The Netherlands
[d] Katholieke Universiteit Leuven, Division Agricultural and Food Economics, Willem de Croylaan 42 Box 2424, BE- 3001 Leuven, Belgium
[e] World Agroforestry Centre (ICRAF) Regional office for South Asia, CG Block, 1st Floor, National Agricultural Science Centre, Dev Prakash Shastri Marg, Pusa, New Delhi - 110 012, India

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[*] Corresponding author. Tel.: +32 (0) 16 329726; Fax: +32 (0) 16 329760;
E-mail address: bart.muys@biw.kuleuven.be (B. Muys)

Abstract

The interest in using *Jatropha curcas* L. (JCL) as a feed stock for the production of bio-diesel is rapidly growing. The properties of the crop and its oil have persuaded investors, policy makers and Clean Development Mechanism (CDM) project developers to consider JCL as a substitute for fossil fuels to reduce greenhouse gas emissions. However, JCL is still a wild plant of which basic agronomic properties are not thoroughly understood and the environmental effects have not been investigated yet. Gray literature reports are very optimistic on simultaneous wasteland reclamation capability and oil yields, further fueling the *Jatropha* bio-diesel hype. In this paper, we give an overview of the currently available information on the different process steps of the production process of bio-diesel from JCL, being cultivation and production of seeds, extraction of the oil, conversion to and the use of the bio-diesel and the by-products. Based on this collection of data and information the best available practice, the shortcomings and the potential environmental risks and benefits are discussed for each production step. The review concludes with a call for general precaution and for science to be applied.

Keywords

Jatropha curcas; physic nut; cultivation; bio-energy; energy conversion, bio-fuel; environmental impact; greenhouse gas balance; land use impact; human health

1. Introduction

In a context of growing interest for renewable energy sources liquid bioenergy production from vegetable oils is proposed as one of the possible options to reduce greenhouse gas (GHG) emissions. Against this background bio-diesel production from *Jatropha curcas* L. (JCL) has become a booming business. The oil produced by this crop can be easily converted to liquid bio-fuel which meets the American and European standards [1-2]. Additionally, the press cake can be used as a fertilizer and the organic waste products can be digested to produce biogas (CH_4) [3-7]. The plant itself is believed to prevent and control soil erosion or can be used as a living fence or to reclaim waste land [8-12]. JCL is still a wild plant, which can grow without irrigation in a broad spectrum of rainfall regimes, from 250 up to 3000 mm per annum [13]. Furthermore, JCL is reported to have few pests and diseases [5,10], but this may change when it is grown in commercial plantations with regular irrigation and fertilization [14]. Based on these interesting properties, potentials and hyped claims, a lot of investors, policy makers and Clean Development Mechanism project developers are interested in JCL to tackle the challenges of energy supply and GHG emission reduction [12,15].

The essential minimum requirements for bio-fuels to be a more sustainable alternative for fossil fuels is that they should be produced from renewable raw material and that their use has a lower negative environmental impact [16]. Closer investigation is needed in order to conclude if both minimum requirements are fulfilled. Different sustainability evaluation tools and environmental impact assessment tools are available to investigate if an agricultural production process meets these requirements [17]. Life cycle assessment (LCA) is such an instrument and has already shown its utility to evaluate the environmental balance of bio-fuel from other vegetable oils [18-21]. Using LCA or any other sustainability evaluation tool will need input data as a start to perform the evaluation or the assessment.

In this paper we present a state-of-the-art literature review of the whole JCL bio-diesel production process and use. For each production step the available published information on inputs and outputs is compiled. This collection of data and information enables us to discuss (*i*) the actual best practice(s) for production of JCL bio-diesel, (*ii*) the most persistent shortcomings, and hints of remedies and (*iii*) on the most prominent potential environmental issues, using a limited LCA approach (energy balance, greenhouse gas balance, land use impact). Information was compiled not only from peer-reviewed literature, but also from reports and conference proceedings. Doing so we could cover a wider range of information, which allowed us to obtain quantitative data presented as ranges, averages and standard deviations.

2. Botanical description of *Jatropha curcas* L.

JCL or Physic nut is a small tree or large shrub, up to 5-7 m tall, belonging to the *Euphorbiaceae* family, with a soft wood and a life expectancy of up to 50 years. The plant has its native distributional range in Mexico, Central America, Brazil, Bolivia, Peru, Argentina and Paraguay [22], although nowadays it has a pantropical distribution [12] with distinct JCL seed provenances. The plant develops a deep taproot and initially four shallow lateral roots [9]. The taproot may stabilize the soil against landslides while the shallow roots are alleged to prevent and control soil erosion caused by wind or water, but this potential has not been investigated scientifically. The leaves are smooth, 4-6 lobed and 10-15 cm in length and width. The plant is monoecious and the terminal inflorescences contain unisexual flowers. The ratio of male to female flowers ranges from 13:1 to 29:1 [6,23] and decreases with the age of the plant [24]. Normally JCL flowers only once a year during the rainy season [23]. In permanently humid regions or under irrigated conditions JCL flowers almost throughout the year [9]. After pollination, the inflorescences form a bunch of green ellipsoidal fruits [6]. The blackish seeds of most provenances contain toxins, such as phorbol esters, curcin, trypsin inhibitors, lectins and phytates, to such levels that the seeds, oil and seed cake are not edible without detoxification (see e.g. Becker and co-workers [25-33]).

3. *Jatropha* cultivation

The cultivation of JCL trees for the production of oil-bearing fruits is considered the first production step towards bio-diesel production (Fig. 1). The main inputs are land area including the prevalent site characteristics, plantation establishment practices and plantation management practices including the production and use of all machines, infrastructure and energy (transport, power, etc.) needed for those inputs. The outputs are the seeds, other biomass elements including the husks, and GHG emissions. In this analysis, we did not consider erosion or nutrient losses to surface water as these are highly dependent on site conditions and difficult to generalize.

(Insert Fig. 1)

3.1. Site requirements

JCL's high ecological adaptability [9] allows it to grow in a wide range of conditions. As a succulent that sheds its leaves during the dry season, JCL is well adapted to semi-arid conditions, although more humid environmental conditions show to result in better crop performance. The documented seed provenances show average temperatures between 20°C and 28C° [9,31], but its occurrence has been observed in a rainfall range between 250 mm and 3000 mm [13]. JCL can tolerate high temperature extremes, but generally fears frost, which causes immediate damage [9,34]. In Nicaragua, it has an altitude range from sea level up to 1800m [13]. The plant is not sensitive to day length [9].

JCL can grow in a wide range of soils. Well drained sandy or gravelly soils with good aeration are preferred [9,13]. In heavy soils, root formation will be hampered [9]. JCL should never be planted on soils with risk of even ephemeral water logging, such as Vertisols or other heavy clay soils [35,36]. Soil depth should be at least 45 cm [34] and surface slope should not exceed 30° [6]. JCL has low nutritional requirements but the soil pH should not exceed 9 [6,36] and on very acidic soils JCL might require some Ca and Mg fertilization. JCL is well adapted to marginal soils with low nutrient content [9], but in order to support a high biomass production the crop shows a high demand for nitrogen and phosphorus fertilization [13]. Mycorrhiza assisting with the uptake of phosphorus and micro-elements were found on the root system [8,10,34,37]. Mycorrhiza inoculated JCL showed a 30% increase in both biomass and seed production seven months after plantation of one-year-old saplings [6].

3.2. Propagation and plantation establishment

JCL is easily propagated by generative (direct seeding or pre-cultivated seedlings) and vegetative (direct planting of cuttings) methods [9,10,38]. The crop shows high initial establishment success and survival [39]. For quick establishment of living fences and plantations for erosion control, direct planting of cuttings is considered easier [9], although JCL plants propagated from cuttings do not develop a taproot. The plants only develop thin roots unable to grow deep in the soil, which makes the plants more susceptible to uprooting by wind [40]. In agroforestry and intercropping systems direct seeding should be preferred over pre-cultivated JCL plants, as the taproot of directly seeded plants is believed to penetrate in deeper soil layers [41] where it can assess extra nutrient resources and where it competes less with the roots of the other crops [9]. If early seed yields are to be achieved, direct planting of stakes can be used as well [9].

Recommandations on vegetative propagation vary. Cuttings of 25-30 cm length from one-year-old branches [34] or longer cuttings up to 120 cm [38] are among the options. Kaushik & Kumar [42] report that the survival percentage depends on the origin of the source material (top, middle or base of the branch) and the length and diameter combination of the cutting [42]. Their study showed a survival percentage of 42% when the top of the branches were used as cuttings, while cuttings from the middle (72%) and base (88%) showed significantly better survival results. The product of the length and diameter dimensions of the used cuttings had a positive correlation on the survival percentage as well. The longer and larger a cutting, the higher its survival rate. Survival percentages higher than 80% were obtained for the length – diameter combinations from 105 – 2.5 cm, 45 – 3.5 cm, 45 – 4.5 cm and onwards [42]. Cuttings can be planted directly in the field or in nursery beds or polyethylene bags for first root development [9,34,38,42]. They have to be placed 10-20 cm into the soil depending on their length and diameter. Planting of cuttings is best done in the rainy season [43].

Using generative propagation, direct seed sowing is recommended at the beginning of the rainy season, after the first rains when soil is wet, because it helps to develop a healthy taproot system [34]. Seedlings can be pre-cultivated in polythene bags or tubes or in seed beds under nursery conditions. The use of plastic bags or tubes is observed to induce root node formation and spin growth [40]. In the nursery, seeds should be sown three months before the rainy season in a soil with a high concentration of organic material (sandy loam soil – compost ratio 1:1 [42]; in case of more heavy soils, sand is added: sand – soil – compost ratio 1:1:2 [34]; sand – soil – farm yard manure ratio 1:1:1 [35]) and should be well watered [38]. Pre-soaked seeds (24 hours in cold water) germinate in 7-8 days in hot humid environment whereas the process continues for 10-15 days [34]. A study on the germination enhancement of JCL seeds showed best results for pre-soaking in cow-dung slurry for 12 h (96% germination). The traditional 24 h cold water treatment showed 72% germination. Nicking yields similar germination rates (pers. obs.), while pretreatments using hot water or H_2SO_4 (0.5 M) do not enhance germination [44].

At the onset of the rains the seedlings can be planted in the field. Planting distances of 2 × 2 m (2500 plants ha^{-1}), 2.5 × 2.5 m (1600 plants ha^{-1}) or 3 × 3 m (1111 plants ha^{-1})

are common practice [9]. Kaushik and Kumar [42] propose to use wider spacing patterns (4×2 m and 4×3 m) and agroforestry systems (spacing 5×2 m and 6×6 m) to optimize the yield of individual JCL plants. In 2.5-year-old plantations it was observed that with increasing spacing, seed yield tree^{-1} increased significantly, while the seed yield ha^{-1} decreased [45]. The recommended spacing in hedgerows for soil conservation is 15-25 cm within and between (in case of double fence) rows (4000-6700 plants km^{-1}) [10].

Field preparation for oil production plantations mainly consists of land clearing and preparation of the planting pits for the pre-cultivated plants. Although planting can be done without any clearing, for oil production purpose it is advisable to clear the land at least partially [34]. Tall trees can be left, but shrubs and bushes that cover the soil should be cut. Ploughing the field belongs to the possibilities as well [34]. After clearing, planting pits of 30-45 × 30-45 × 30-45 cm^3 should be dug prior to the rainy season [34,35]. For good establishment the pits are best refilled with a mixture of the local soil, sand, organic matter such as compost and/or artificial fertilizer.

The best moment for planting is the warm season — if watering can be provided — or at the onset of the rains [10]. Gour [34] poses that seedlings require irrigation, especially during the first 2-3 months after planting. Of course, the water demand depends on local soil and climatic conditions.

3.3. Tending practice of the plantation

Besides propagation and spacing some publications mention weeding and pruning [9,10,46,47]. Recent publications [34,35,42] sketch a more complete view on management and cultivation activities. Regular weeding operations should free the field from competitive weeds. Uprooted weeds can be left on the field as mulch. Pruning and canopy management is presented as an important crop architectural intervention, which is believed to help the production of more branches and to stimulate abundant and healthy inflorescence, thus eventually enhancing good fruit setting and seed yield [34]. At the age of six months it is useful to pinch off the terminal shoots in order to induce lateral branching [34,42]. Experiments reveal that pruning the main branch at 30 - 45 cm height — depending on the growth rate — is ideal [34]. At the end of the first year, the secondary and tertiary branches should be pinched or pruned to induce more branches. During the second year each side branch should be pruned up to two-thirds of the top portion, retaining one-third of the branches on the plant [34,42]. Pruning should be done in the dry or winter period after the trees have shed their leaves. This will result in a lower and wider tree shape, induce earlier seed production and facilitate manual harvesting. Once every 10 years, the entire plant has to be cut low, leaving a stump of 45 cm. The re-growth will be quick and the trees will start yielding again within about one year. This intervention will induce new growth and help to stabilize the yield [34]. Beside trimming hedgerows and pruning plantations annually, periodic thinning of plantations is proposed as well. Starting from 1600 seedlings per hectare, stand density should be thinned to 400-500 trees per hectare in the final mature stand [10].

It is clear that optimal fertilization and irrigation application can increase the seed and oil yield. However, permanent humid situations and/or situations with high irrigation and fertilizer application can induce high biomass but low seed production. The input levels to optimize the harvest index in given conditions are yet to be quantified. No quantitative data on water need, water productivity and water use efficiency of JCL are available at present. In general application of super phosphate or NPK fertilizer is reported to increase the yield. The optimum application levels of inorganic N and P fertilizers are observed to be variable according to the age of the plantation [48]. On degraded sites JCL plants are found to respond better to organic manure than to mineral fertilizers [8]. Based on the nutrient composition of JCL fruit (compiled by Jongschaap et al. [41]) it can be estimated that harvesting the equivalent amount of fruits for a yield of 1 ton of seeds ha^{-1} results in a net removal of 14.3-34.3 kg N, 0.7-7.0 kg P and 14.3-31.6 kg K ha^{-1}. So fertilization (artificial or organic) at least has to compensate this.

The susceptibility of JCL for pest and diseases is a source of discussion and is believed to depend on the management intensity. Early publications [9,49] already listed numerous pests, diseases and damaging insects observed on JCL. Furthermore it is believed that JCL can transmit the cassava superelongation disease (*Sphaceloma manihoticola*) and is a possible host for African Cassava Mosaic Virus (until now only observed in *Jatropha multifida* L.) [9]. A popular belief is that JCL is not prone to pests and diseases in such extent to cause economic damage. However, in continuous JCL monocultures in India economic damage has already been observed [50]. The major problems in JCL cultivation are caused by the scutellarid bug *Scutellera nobilis* and the inflorescence and capsule-borer *Pempelia morosalis* [50]. Grimm and Maes [49] identified *Pachycoris klugii* (*Scutelleridae*) and *Leptoglossus zonatus* (*Coreidae*) as the key pests in Nicaragua. Other possible pests are the blister miner *Stomphastis* (*Acrocercops*) *thraustica*, the semi looper *Achaea janata* and the flower beetle *Oxycetonia versicolor* [50]. Regular irrigation and fertilizer application is expected to enhance these pest and disease infestations in commercial monocultures [14].

3.4. Seed yield

For best oil yields, the seeds should be harvested at maturity. Seeds are mature if the color of the fruits has changed from green to yellow-brown. Maturity is reached 90 days after flowering [9], but the fruits do not mature all at the same moment. As such the fruits have to be harvested manually at regular intervals [9,35], making this step very labour intensive. The moment and length of harvest period is likely to vary according to the seasonal conditions of the locality [51]. In semi-arid regions the harvest is spread over a period of two months which implies daily or weekly harvests. In permanent humid situations weekly harvest can be necessary all year through. Separation of the seeds and husks can be done manually or mechanically [34].

JCL seed yield is still a difficult issue. Actually the mature seed yield per ha per year is not known, since systematic yield monitoring only started recently. Earlier reported figures exhibit a very wide range (0.4 – 12 t ha^{-1} yr^{-1} [10]) and are not coherent [9] (Fig. 2) and Appendix 1), mainly because of incorrect extrapolation of annual yields of individual trees to ha^{-1} yr^{-1} yields. At present the effect of spacing, canopy management and crown form and surface on the yield is not known, making it impossible to make such extrapolation. Fig. 2 indicates positive trends in the influence of both average annual rainfall and age on the seed yield. Mainly the upper boundary of the yield in function of the rainfall is interesting and shows a clear difference between low rainfall and high rainfall regimes.

(insert Fig. 2)

Yield depends on site characteristics (rainfall, soil type and soil fertility) [8,10,54], genetics [55], plant age [9,56] and management (propagation method, spacing, pruning, fertilizing, irrigation, etc.) [9,34,35]. Information on these yield influencing variables was generally not reported alongside. JCL has not yet undergone a careful breeding programme with systematic selection and improvement of suitable germplasm, which is why it can still be considered a wild plant that exhibits great variability in productivity between individuals. Annual seed production can range from about 0.2 kg to more than 2 kg per plant [8]. For semi-arid areas and cultural wasteland Heller [9] and Tewari [6] propose an achievable dry seed production of 2-3 ton ha^{-1} yr^{-1}, which are confirmed by field data of Francis et al. [8]. When good sites (good soil and average annual rainfall of 900-1200 mm) are claimed and/or optimal management practice is used, 5 ton dry seed ha^{-1} yr^{-1} can be achieved [6,8,13]. Jongschaap et al. [41] conclude to a potential yield range of 1.5-7.8 ton dry seed ha^{-1} yr^{-1}.

As mentioned earlier JCL is a hardy and highly adaptable crop that can grow in marginal soils from an average annual rainfall of 250 mm. As such JCL is capable to reclaim wasteland [57]. But is it able to produce ecologically and socio-economically viable amounts of energy in these barren situations?

Average shell:kernel ratio on mass basis of the JCL seeds is 37:63 (Fig. 3). The kernel mainly contains crude fat and protein and has an average calorific value of 30.4 MJ kg^{-1} (Fig. 4). The shell is mainly composed of fiber and has a calorific value of 19.4 MJ kg^{-1}. Based on these figures the average oil content of dry seed on mass basis is 34.4%.

To date no information on the total biomass production of JCL is at hand. For an irrigated JCL project in Egypt, Henning prospects the future total biomass production to be 80 ton dry matter ha^{-1} (11 ton dry matter ha^{-1} yr^{-1} including seeds) (spacing 2.5 × 2.5 m) representing 5.5 ton CO_2 ha^{-1} yr^{-1} [58]. For Indian wastelands the average annual CO_2 sequestration rate in the standing biomass ha^{-1} is estimated to be ±2.25 tons CO_2 ha^{-1} yr^{-1} (excluding the 2-2.5 tons dry seed yield ha^{-1} yr^{-1}) [8]. The wood density of JCL is reported to range from 0.33 to 0.37 g cm^{-3} [58] although personal observations on young plants (116 days old) noted a wood density of 0.29 ±0.1 g cm^{-3} at the base of the stem.

(Insert Fig. 3)

(Insert Fig. 4)

Makkar et al. [31] reported on 18 different provenances of JCL from countries in West and East Africa, the Americas and Asia including climatic data of these places. Large variations were found in contents of crude protein, crude fat, neutral detergent fiber and ash, but no causal links were analyzed. Recently Kaushik et al. [61] recorded coefficients of variance between 24 provenances of Haryana state, India, which indicate a dominant role of environment over genetics in seed size, seed weight and oil content.

An important by-product of the JCL seed production is the husk which stands for 35-40 % by weight on whole fruit basis [62]. The husk can be used for direct combustion and biogas production [3], but recently it was shown that JCL seed husks are an excellent feedstock for gasification as well [62]. Using an open core down draft gasifier, maximum efficiency was found to be 68.3% at a gas flow rate of 5.5 m^3 h^{-1} and specific gasification rate of 270 kg h^{-1} m^{-2}. The gas had an energy value of 4.6 MJ m^{-3} which is comparable to wood [62].

4. Oil extraction

In the second step of the production chain for bio-diesel, the oil contained in the seeds has to be expelled or extracted. The main inputs for this process, besides the seeds, are the production and use of machines, infrastructure and energy. On the output side, the main products are the JCL oil and the seed or kernel cake, which is an important by-product (Fig. 5). The emissions of GHGs and waste water have to be accounted for in the outputs of the process as well.

The process of gaining oil from oilseeds is as old as mankind, but the possibilities, procedures and means have evolved and are subject of many publications. In the following, only the different extraction options and their performances for JCL seeds are reviewed. For extraction of the JCL oil two main methods have been identified: (i) mechanical extraction and (ii) chemical extraction [28,63].

(Insert Fig. 5)

Prior to oil extraction the JCL seeds have to be dried [38,64]. Seed can be dried in the oven (105°C) or sun dried (3 weeks). Mechanical expellers or presses can be fed with either whole seeds or kernels or a mix of both, but common practice is to use whole seeds. For chemical extraction only ground JCL kernels are used as feed. The shells can be used directly as a combustible by-product or gasification feedstock.

4.1. Mechanical expellers

For mechanical extraction of the oil from the seed, either a manual ram press (e.g. Yenga or Bielenberg ram press) or an engine driven screw press (e.g. Sundhara press [65]) can be used [60,63,66]. Henning [38] stated that engine driven screw presses extract 75-80% of the available oil, while the manual ram presses only achieved 60-65%. Oil extraction efficiencies calculated from data reported in more recent studies [6,63,67,68] are found to generally correspond to these ranges, although the efficiency range of engine driven screw presses can be broadened to 70-80% (Table 1). This broader range corresponds to the fact that seeds can be subjected to a different number of extractions through the expeller. Up to three passes is common practice. Pretreatment of the seeds, like cooking, can increase the oil yield of screw pressing up to 89% after single pass and 91% after dual pass [68]

(Insert Table 1)

4.2. Chemical extraction

Table 2 summarizes the reaction temperature, reaction pH, time consumption and oil yield of different chemical extraction methods tested on JCL. The *n*-hexane method is the most common and results in the highest oil yield, but also takes most time. In aqueous enzymatic oil extraction the use of alkaline protease gave the best results for both available studies [69,70]. Furthermore, it is shown that ultrasonication pretreatment is a useful step in aqueous oil extraction [70].

(Insert Table 2)

Adriaans [73] concludes that solvent extraction is only economical at a large scale production of more than 50 ton bio-diesel per day. Furthermore he does not recommend the conventional *n*-hexane solvent extraction because of environmental impacts (generation of waste water, higher specific energy consumption and higher emissions of volatile organic compounds) and human health impacts (working with hazardous and inflammable chemicals). Using aqueous enzymatic oil extractions greatly reduces these problems [73] as do the use of supercritical solvents (mainly supercritical CO_2) or bio-renewable solvents as bio-ethanol and isopropyl alcohol. Although the new generation *n*-hexane extraction units are very efficient and produce far less environmental burdens than the older units, further research on these alternative solvents is recommended as on their commercial viability. Foidl and Mayorga [74] presented the use of supercritical isopropanol or CO_2 in a continuous mechanical oil extraction system only leaving 0.3% by weight of oil in the cake.

4.3. *Jatropha* oil

The composition and characteristics of the crude JCL oil are given in Table 3. The JCL oil meets the quality standard of rapeseed as a fuel [60].

(Insert Table 3)

It is important to note that the values of the free fatty acids, unsaponifiables, acid number and carbon residue show a very wide range, although it is a small data set. This indicates that the oil quality is dependent on the interaction of environment and genetics. As for the seed size, seed weight and oil content [61], it is believed that also for the oil quality the environmental conditions have a larger impact than the genetics. More research is necessary. Project developers and decision makers should be aware of these wide ranges, because these above-mentioned characteristics are important properties for the further processing of the oil into bio-diesel [86-88].

The JCL oil contains more than 75% unsaturated fatty acid, which is reflected in the pour and cloud point of the oil. The fatty acid composition of JCL oil is dominated by oleic acid (C18:1) and linoleic acid (C18:2) (Fig. 6). The maturity stage of the fruits at the moment of collection is reported to influence the fatty acid composition of the oil [89].

(Insert Fig. 6)

4.4. *Jatropha* seed cake

The average crude protein content of the seed cake is 58.1% by weight and has an average gross energy content of 18.2 MJ kg^{-1} (Fig. 7).

(Insert Fig. 7)

In case of mechanical oil extraction from whole seeds, the oil content of the seed cake will be higher, due to the lower efficiency of the expellers. Based on the extraction efficiencies discussed above and the average oil content of the whole seed (34.4% on a mass basis), the seed cake will contain 9 – 12 % oil by weight. This content will of course influence the gross energy value of this cake as well.

Next to the high quality proteins (Fig. 7) this cake contains various toxins and is therefore not usable as fodder [8]. However, the raw kernel or seed cake can be valuable as organic nutrient source, as it contains more nutrients than both chicken and cattle manure [8]. Table 4 gives an overview of experiments which show that JCL seed cake is useful as fertilizer. The presence of the aforementioned bio-degradable toxins, mainly phorbol esters, makes the fertilizing cake simultaneously serve as biopesticide/insecticide and molluscicide [8,91]. Although the phorbol esters decompose completely within 6 days [91] it is advisable to check the absence of phorbol esters in the crops grown on JCL cake fertilized land, certainly crops for human consumption. Heller [9] warns about phytotoxicity of over-application of JCL cake. One study showed phytotoxicity to tomatoes, expressed in reduced germination, when high rates of up to 5 ton ha^{-1} are applied.

(Insert Table 4)

The cake can serve as feed for biogas production through anaerobic digestion before using it as a soil amendment as well. Staubman et al. [4] obtained 0.446 m^3 of biogas, containing 70% CH_4, per kg of dry seed press cake using pig manure as inoculum. Radhakishna [7], using specific developed microbial consortia as inoculum, achieved 0.5 m^3 biogas kg^{-1} of solvent extracted kernel cake and 0.6 m^3 biogas kg^{-1} of mechanically de-oiled cake. Other organic wastes of JCL can be digested. For example, Lopez et al. [3] showed that biogas could be produced from JCL fruit husks.

The fact that JCL seed cake can be used for different purposes makes it an important by-product. Recycling of wastes as a fertilizer can help to reduce inputs needed for both JCL cultivation and other agricultural cultivation or it can produce extra energy in the form of biogas. Digesting the cake, and bringing the effluent back to the field is thought to be the best practice at present from an environmental point of view. A number of questions concerning the long-term and cumulative impacts of JCL seed cake on soils have not been addressed. In the event that detoxification becomes viable, the use as animal feed will be more beneficial.

5. Production of bio-diesel

Vegetable oil can be used as base for liquid engine fuel in various ways (straight vegetable oil, oil blends, pyrolysis, micro-emulsification, transesterification). All general problems and benefits and all these procedures of using vegetable oils as liquid engine fuel, are the subject of numerous publications [86-88,95-98]. In this section only the published experiences with JCL oil are reviewed.

JCL oil is mainly transesterified to (m)ethyl esters (bio-diesel) and glycerol. Taking JCL bio-diesel as the end product transesterification should be considered the next step in the production process (Fig. 8). Glycerol is an important by-product. It can be burned for heat or be used as feedstock in the cosmetic industry. But using JCL oil as a bio-fuel does not always include an extra unit process. Several publications [63,67,76,80,81,99] report the use of the pure JCL oil or JCL oil blends (see further).

(Insert Fig. 8)

5.1. Transesterification

Although the transesterification process is quite straightforward, the genetic and environmental background of the produced oil might require modification of the input ratios of the alcohol reagent and reaction catalyst as well as alterations to reaction temperature and time, in order to reach optimal bio-diesel production results. The optimal inputs for the transesterification of JCL oil (3.1% free fatty acids and acid number 6.2 mg KOH g^{-1}) are identified to be 20% methanol (by mass on oil basis) (molar ratio methanol:oil ≈ 5.5:1), 1.0 % NaOH by mass on oil basis [83]. Maximum ester yield is achieved after 90 minutes reaction time at 60°C [83]. Optimal conversion of JCL oil with high free fatty acids (14%) and high acid number (28 mg KOH g^{-1}) needs pretreatment reaction with methanol (molar ratio methanol:oil ≈ 6.5:1) using H_2SO_4 as catalyst (1.43%)

during 88 minutes at 60°C. After pretreatment a maximal conversion rate of more than 99% was achieved by transesterification with methanol (molar ratio methanol:oil ≈ 4:1) and 0.6% KOH by weight during 24 minutes[2].

Given the variability the best practice to maximize ester yield, is to determine the optimal inputs of oil samples per oil batch that has to be transesterified. The characteristics of the resulting JCL (m)ethyl esters generally meet the American and European standards [1,2] (Table 5).

(Insert Table 5)

Recently more advanced transesterification procedures are tested on JCL oil as well. Table 6 summarizes the key inputs and outputs of these methods.

(Insert Table 6)

6. Use of the *Jatropha* oil

Jatropha oil has various uses. Apart from its use as a liquid fuel, the oil has been used to produce soap and biocides (insecticide, molluscicide, fungicide and nematicide) [50]. The oil can be directly used in older diesel engines or new big motors running at constant speed (e.g. pumps, generator). Blending with fossil diesel and/or other fossil fuels belongs to the options as well. The oil can also be transesterified into JCL (m)ethyl esters that can be used in conventional diesel engines or diesel engines with adapted parameters.

6.1. Direct use of the oil

Tests with a low heat rejection diesel (LHR) engine showed that the use of pure JCL oil results in a higher brake specific energy consumption (BSEC), lower brake thermal efficiency (BTE), higher exhaust gas temperature (EGT) and lower NO_x emissions in comparison with fossil diesel [99]. Preheating and increasing the injection pressure decreased BSEC, increased BTE, increased EGT and increased NO_x emissions only marginally [99]. Kumar et al. [80] compared the use of JCL oil and fossil diesel in a single cylinder 4 stroke water cooled diesel engine and concluded that the soot (hydrocarbon) emission is higher with JCL oil as compared to fossil diesel. At maximum output an increase from 100 ppm, for fossil diesel, to 130 ppm, for JCL oil, was measured and similar trends were observed in the case of CO emissions. Smoke level was higher with JCL oil (4.4 BSU) compared to fossil diesel (3.8 BSU) as well. Furthermore they observed an increase in ignition delay and combustion duration with JCL oil in comparison to fossil diesel [80].

6.2. Use of transesterified oil

The use of the methyl ester of JCL resulted in a soot emission of 110 ppm compared to 100 ppm for fossil diesel and in increased CO emissions [80]. *Jatropha* methyl ester (JME) approached the smoke levels (4.0 BSU) of fossil diesel level (3.8 BSU). JME was also observed to decrease the BTE and volumetric efficiency, to increase the ignition delay and combustion duration [80]. In addition, the study of Prasad et al. [99] showed higher BSEC for JME use than for conventional diesel use. Since the calorific value of JME is lower than conventional diesel, this observation implies that the JME fuel consumption will be higher than conventional diesel as well. Prasad et al. [99] conclude that the use of transesterified JCL oil achieves similar results as the use of fossil diesel, although it causes less NO_x emissions. Furthermore, transesterified JCL oil shows little or no additional engine corrosion as compared to fossil diesel [103].

6.3. Use of blends

The use of pure JCL oil – fossil diesel blends has been tested in a single cylinder, water cooled open combustion chamber diesel engine [81]. Brake specific fuel consumption (BSFC) and EGT of the blends were found to be higher compared to fossil diesel and tended to increase with increasing proportion of JCL oil in the blend. The opposite applies for the BTE. However, blends of 30% JCL oil and 70% fossil diesel by volume and of 40% JCL oil and 60% fossil diesel by volume showed BSFC and BTE close to the values of fossil diesel. Both BSFC and BTE were found to be acceptable up to 50% by volume of JCL oil [81]. Furthermore, the study concluded that the long-term durability of the engine using bio-diesel as fuel requires further study.

Kumar et al. [80] also tested JCL oil – methanol blends and dual fuel operation. Blending JCL oil with methanol increases the BTE, lowers the HC and CO emissions and reduces smoke levels, but the blend could not reach the results of JME. Furthermore, the blend increased ignition delay [80]. The dual fuel operation with methanol induction and

JCL oil as the pilot fuel resulted in a significant increase in BTE (although, not achieving the JME results) and showed lowest smoke and NO levels. The penalty is an increase in HC and CO emission [80].

In a Lister model engine (single cylinder, air cooled, direct injection, four stroke diesel engine) a blend of 2.6% JCL oil and 97.4% fossil diesel by volume showed lowest BSFC and highest BTE [63] in comparison to fossil diesel and blends with higher JCL oil portion. In the oil extraction procedure of the used JCL oil a small portion of water was added which emulsified the JCL oil. This resulted in a reduction of EGT and, as such, a reduction in NO_x emission with increasing portion of JCL oil in the blend [63]. Attention is to be paid to the water content of the used fuel as it causes oxidation inside the injection equipment [60].

6.4. Alternative engine technology

Retarding the injection timing with enhanced injection rate of a single cylinder, constant speed, direct injection diesel engine, operating on neat JCL oil, showed to improve the engine performance and emission level significantly [76]. The measured emissions were even lower than fossil diesel. At full output HC emission level was observed to be 532 ppm against 798 ppm for fossil diesel, NO level was 1163 ppm against 1760 ppm and smoke was reduced to 2.0 BSU against 2.7 BSU. However, the achieved BTE with JCL oil (28.9%) was lower than with fossil diesel (32.1%) [76].

From the above summarized studies it can be concluded that JME generally achieves the best results in comparison to the use of pure JCL oil, straight or in a blend, although the scope for the use of the pure JCL oil can not be underrated. Certainly in tropical developing countries the use of pure JCL oil, straight or as a blend, is believed to have great potential [60]. The diesel engines in those countries, including those of old four-wheel-drive vehicles, rely on older technology, are easier to adapt to the characteristics of the used fuel and the tropical temperatures lower the viscosity of the oil [60]. Stationary diesel engines at low speed, such as irrigation pumps and electricity generators, are believed to be suitable to pure JCL oil without a too high environmental burden. Pre-chamber diesel engines are more suitable for the use of pure oil than direct injection engines, but simple conversion to a direct injection two tank system can overcome their problems [60]. Despite the reported difficult use of pure vegetable oils [86,87,95,98], there is still scope for improvement. Further research is recommended.

7. Discussion

7.1. Best available practice for the production of JCL bio-diesel and shortcomings

In this discussion an intuitive interpretation is given to the collected data and information on *Jatropha* bio-diesel production and use. The collected data are evaluated with the objective of describing best available practice for a production system in which JCL oil and/or bio-diesel is the main product.

7.1.1 Jatropha cultivation

Aiming mainly at oil production, block plantations are probably the best option. How such plantation is best established, is subject to much discussion yet. According to Heller [9] plants propagated by seeds are preferred for establishment of long living plantations for oil production. This can be supported by the fact that vegetative propagated plants do not develop a taproot, but only a superficial root carpet [40] which leads to more superficial water and nutrient competition. The taproot of generatively propagated plants will have more access to nutrients from deeper soil layers [41] and can reach deeper water resources.

The selection of basic material is a critical step (in case of vegetative as well as generative propagation). Basing this selection on successes of controlled breeding programmes would be the best option, but present results are not yet sufficient. In JCL provenances available in India only modest levels of genetic variation were observed, while wide variation was found between the Indian and Mexican genotypes [104]. This shows the need to characterization of provenances with broader geographical background [104]. Best available practice at the moment is to use planting material obtained from the best performing trees of the best performing provenance available in the location of interest. Trees with an annual yield above two kg dry seeds and seed oil content higher than 30% by weight can be considered a good source [34]. In generative propagation the selection of the heaviest and largest seeds for sowing results in significant growth increase of JCL seedlings [105]. Although germination rates, certainly after easy applicable pretreatments of the seeds (nicking, cold water), are quite high and although nursery bags can hamper initial root formation, we would intuitively recommend plantation establishment through planting of seedlings. As such the plants can be sufficiently protected in their initial growth stage, when they are still quite susceptible for weather extremes or other possible events. Using seedlings one has more control on the uniformity of the plantation as well. Further the planting pits will guarantee a good establishment in the soil. The main drawback of this practice is the influence of the polythene bags and pots on the root structure [40].

Due to root competition for water the optimal spacing is believed to be a function of rainfall, where wider spacing should be used in semi-arid environments and denser plantations can be appropriate for sub-humid environments. It was noted that spacing of plants is a trade off between biomass and fruit production. A narrow spacing will lead to fast canopy closure which results in higher water and light competition and lower fruit:biomass ratio in the mature stadium. When planting JCL for live-fencing or hedges for soil conservation a dense biomass is needed and close spacing is appropriate. When the aim of the plantation is oil production, seedlings should be planted wide enough to ensure high seed yields in the mature stage, but close enough to avoid unacceptable loss of photosynthetic capacity in the juvenile stage. Thus, optimum spacing can only be recommended after at least 5 years consecutive growth and yield observations and this in different environmental conditions and using different provenances. The authors feel that the best available practice at this moment is to start with a densely spaced block plantation and gradually remove rows or individuals (thinning) according to the plant performances.

Contrary to popular believe, it should be made clear that plantations aiming at oil production will need fertilization (artificial or organic). Fertilizer at least needs to compensate the nutrient removal due to harvest or management practice (pruning – if not used as propagation material). Irrigation will depend on the climatic conditions of the location. The minimum annual average rainfall at which JCL is known to yield a harvestable amount of seeds is 500-600 mm yr^{-1}. So, simultaneous reclamation of barren lands and bio-diesel production will inevitably imply use of fertilizer and irrigation. Although there are already several fertilization trials available [48,94] there is still insufficient information to account the nutrient need for specific environmental and genetic setups. The same applies for irrigation.

Reliable yield prediction still forms the biggest problem. At present there are no reliable field data on the dry JCL seed yield ha^{-1} yr^{-1} in a given set of conditions and at a certain level of input. It is believed that for well managed plantations in good environmental conditions a yield expectation of 4-5 ton dry seed ha^{-1} is reasonable. In order to tackle this knowledge gap, it is absolutely necessary to systematically monitor the year-to- year seed yield in operational plantation conditions along with the influencing factors. Furthermore, research is necessary to quantify the causal effects of each of the influencing factors on the yield. It is important to give special attention to the interactions between the environmental and management requirements and the influence of the different provenances. Issues to address at the crop level are biogeochemical cycling, water use efficiency, drought resistance, total biomass production, pest management (inclusive hosting and transmitting capacity of pest and diseases infesting other crops), issues on invasiveness and land suitability of JCL.

JCL is still a wild plant with a wide variation in growth, production and quality characteristics. In order to work towards high yielding bio-diesel plantations, the best suitable germplasm has to be identified for different cultivation situations. This implies characterization of provenances with broader geographical background in order to widen the genetic base of JCL. An intensive inventory of the finalized and ongoing provenance trials will give an idea of the available material and will indicate where more provenance trials are needed (this is ongoing in the Global *Jatropha curcas* evaluation, breeding and propagation programme of Plant Research International, Wageningen with principal investigator R.E.E. Jongschaap). Based on such information, systematic and selective breeding should be carried out in order to develop high and early yielding hybrids with high oil yield in given site conditions. Recently a method has been developed for identification of superior lines by assessing the phenotypic traits of JCL plants recorded *in-situ* [106]. According to the authors this method facilitates the selection of promising accessions for multi-location evaluation and hastens the process of utilization of germplasm.

In short it can be stated that more systematic research and complete reporting is necessary on the input-responsiveness of the production at different levels of inputs, including environmental, as well as genetic, physical, chemical and management inputs (e.g. spacing, soil conditions, pruning, fertilizer, irrigation). Seed yield and biomass production in different environmental and abiotic setups, using different provenances or accessions, applying different levels of the different inputs should be monitored in order to discover the input-responsiveness of those different inputs as well as the interactions between the different inputs and the interaction between the environmental and genetic setups and the different inputs.

7.1.2 Oil Extraction

The choice of extraction method is clearly dependent on the intended scale of the activity. The two extraction procedures, mechanical and chemical, are quite well established, although there is still scope for further research. Both of them have their advantages and disadvantages with respect to scale suitability, centralization, extraction efficiency and environmental and health risks. Further research should investigate efficiency improvement of mechanical oil extraction, the applicability of alternative solvents as supercritical CO_2, bio-ethanol and isopropyl alcohol and their economical viability. Decentralized processing technology should be considered as well [8]. Such development should go in synergy with the transesterification setup.

The seed/kernel cake is a very important by-product, which we recommend to be brought back on the JCL field. Although the use of the cake as fertilizer is already common practice, there are still questions to be addressed. More trials are needed where the growth effect on different kinds of crops are monitored (including phytotoxicity and bio-safety effects). The impacts on the soil structure, water holding capacity, soil decomposition, organic matter content and soil biological activity should be brought under detailed investigation as well.

7.1.3 Production and use of JCL bio-fuel

The production of bio-diesel from vegetable oils in general is well documented. Crucial research and development options lay in the maximization of the transesterification efficiency at minimal cost. An important issue in this is the improvement in the catalytic process, certainly the recovery and the reuse of the catalyst [8]. As part of the option of decentralized processing units, low-cost, robust and versatile small scale oil transesterification designs should be developed [8].

The choice of using JCL bio-diesel (i.e. methyl esters) or the JCL oil depends on the goal of the use (e.g. electricity or transport) and the available infrastructure. Studies show that transesterified JCL oil achieves better results than the use of pure JCL oil, straight or in a blend, in unadjusted diesel engines. Changing engine parameters shows considerable improvement of both the performance and the emission of diesel engines operating on neat JCL oil. More trials on the use of straight JCL oil in different diesel engine setups should be tested and investigated. Accurate measuring and reporting on emissions contributing to global warming, acidification, eutrophification, photochemical oxidant formation and stratospheric ozone depletion is very relevant. The long term durability of the engines using bio-diesel as fuel requires further study as well.

7.2. Environmental issues

As mentioned before there are different tools available for assessment of environmental impacts or evaluating environmental sustainability. In this section we will discuss the environmental issues of JCL production and use through a limited life-cycle approach.

In LCA all inputs and outputs of each step of the complete production cycle are inventoried and the calculated impacts are compared with a reference system. In this case we propose a reference system producing the same amount of energy based on fossil energy sources [107-110]. Most LCA studies of bioenergy from agriculture and forestry are limited studies focusing on the energy balance and the global warming potential [107-114] while there are several other impact categories to address [115]. Land use impact is one of those that is rarely included, although “flows” of land area, water, vegetation and biodiversity are certainly as important for the viability and sustainability of production systems occupying substantial portions of land [116-118]. The land use impact assessment will give us an idea of the renewable character of vegetable oil or bio-fuel from the production process of interest.

Based on the unit processes described in the former sections we discuss the potential life cycle impacts of JCL biofuel production on (*i*) energy balance, (*ii*) global warming potential and (*iii*) land use.

7.2.1 Energy balance

The life-cycle energy balance of the bio-diesel production from JCL is reported to be positive [64,119] (Fig. 9). Note that Fig. 9 gives energy input values after allocating the total energy requirement of the whole process to the different products (end-product and by-products). This allocation is a pro-rata distribution of input energy among the products based on the energy content of those products. In Fig. 9 the energy input was distributed among the JME (end-product), glycerin (by-product of transesterification) and seedcake (by-product of oil extraction). The other by-products (wood, fruit husks) are not included in this allocation because the use of these by-products in an energy-efficient way is not common practice. The use of allocation is only justified if the by-products to which input energy is allocated are effectively used in reality. In case none of the by-products are used, the energy balance will be only slightly positive (886 MJ input for 1000 MJ JME output [119]) or even negative. On the other hand, if all by-products (including wood and fruit husks) would be used efficiently this total input of 886 MJ results in a total output of 17235 MJ [119], resulting in a allocated energy input of 160 MJ per 1000 MJ JME (own calculations based on [119]).

(Insert Fig. 9)

Fig. 9 shows the energy balance of high and low JCL cultivation input. The difference between the two applied cultivation intensities is clear. In the low intensity system the JCL cultivation step stands for 17% of the total primary energy input, while the step accounts for 38% of the total energy input in the high intensity systems. Irrigation and fertilizer are the most energy intensive cultivation practices. Irrigation stands for 46% of the total energy input in the JCL cultivation; while fertilizer consumes 45% [119]. In both available studies the transesterification step is shown to be a big energy consumer (Fig. 9). The oil extraction step accounts for a similar share (± 8%) of the total life cycle primary energy requirement in both studies (Fig. 9).

Based on the available results it can be expected that the life cycle energy balance of bio-diesel is generally positive. How positive the balance is in reality, will mainly depend on how efficient the by-products of the system are used. The available information furthermore shows that energy balance improvement options lay in the transesterification and cultivation step.

Transesterification shows to be the biggest contributor in the allocated energy requirement for the bio-diesel end product (Fig. 9). This would mean that the use of the crude oil as an end-product would improve the energy balance significantly. However, the engine combustion of pure JCL oil is less energy efficient [99] and still causes some engine problems [87]. In case of using old, stationary, low and constant speed engines , the lower energy efficiency of the pure oil compared with the transesterified oil, will probably be of no significance.

The energy requirement shows to vary a lot depending on the cultivation intensity (Fig. 9). The comparison between the two limited LCA case studies performed on JCL [64,119] shows that intensified cultivation does not always completely pay off in an extra energy production in the form of bio-diesel [120]. A significant energy balance improvement option lies in the optimization of the input-yield relationship, as discussed above.

7.2.2 Impact on global warming potential

Both available LCA exercises [64,119] showed positive results on the GHG requirement of the production of bio-diesel from JCL in comparison to fossil diesel. The largest GHG contributors of the production process are irrigation (if applied: 26% [119]), fertilizer (if applied: 30% [119]) and transesterification (24% [119] and 70% [64] depending on the applied cultivation intensity).

Prueksakorn and Gheewala [119] found that 90% of the total life cycle GHG emissions are caused by the end-use. They calculated that the global warming potential of the production and use of JCL bio-diesel is 23% of the global warming potential of fossil diesel.

In general the impact on the global warming potential can be expected to be positive in comparison to the use of fossil diesel. It is clear that intensification of the cultivation step and transesterification will increase the GHG requirement of the production process. But, since Prueksakorn & Gheewala [119] consider the end use as the main contributor (90% of the total) this increase can only thought to be marginal in the overall life cycle impact on the global warming potential. However, both limited LCA case studies do not account for N_2O emissions due to N fertilization. The global warming potential of N_2O is 296 times higher than an equal mass of CO_2 [121]. According to the IPCC the N_2O release is equal to about 1% of the nitrogen input from mineral fertilizer or biologically fixed N [122]. As the reduction of global warming potential is one of the main aims of the JCL bio-diesel system, this confirms the research need on input-responsiveness of the JCL cultivation step. For the use of the by-products the same applies for both GHG balance and energy balance.

The removal of (semi-) natural forest for the introduction of JCL, on the other hand, is expected to have a significant negative effect on the GHG balance of the whole life cycle. The caused emission due to removal of (semi-) natural forest is a heavy burden on the initial GHG investment which will take a significant time span before it is paid back with the GHG emission reduction of the use of the bio-diesel.

7.2.3 Land use impact

Land use impact assessment methodologies within LCA are still being discussed, but there is consensus about the fact that land use change and land use occupation impacts on soils and local biodiversity have to be assessed [117]. No assessment of these issues has been executed for JCL so far, but it is expected that land occupation impact of JCL on the soil will be positive. JCL is observed to improve soil structure [123], is strongly believed to control and prevent soil erosion and sequestrates carbon. No information is available on nutrient cycles and the impact on soil biological live. The growing concern on these issues must be checked by focused research. It is important to note that this occupation impact will heavily depend on the applied cultivation system and intensity. Heavy machinery and high fertilizer application are expected to be the main drivers towards a negative impact.

Being an exotic species in most actual growing areas, the impact of land use change towards JCL on biodiversity is expected to be negative, although this will largely depend on the mix of land use which is replaced by JCL and on how JCL is cultivated. Impact on biodiversity will be especially negative when (semi-) natural systems such as dryland forests are cleared. Using JCL on barren wastelands has even potential to help restoring the local biodiversity. Using JCL as intensive monoculture will have severe impacts on the local biodiversity, while using JCL as live fence or in intercropping and agroforestry systems might not have a significant impact. However, there are some reports stating that JCL is an invasive species [124-126]. JCL is considered and treated as invasive in South Africa and as weedy in Australia [127]. However, no studies have been performed to quantify the allelopatic effects of JCL on native vegetation.

It is obvious that the main concern for this impact category is in the JCL cultivation unit process. Within this cultivation the mix of original land use, the used cultivation system and the applied cultivation intensity will be the most important influencing factors.

7.2.4 Issues in other impact categories

Due to the toxicity of the JCL seeds and oils, some attention should be paid to the human health and work environment impact categories. The fruits contain irritants affecting pickers and manual dehullers [128]. Although JCL has a very long history as medicinal plant, accidental intake of seeds and/or oil can cause severe digestion problems. For safety reasons, intercropping edible crops with JCL should only be recommended during the period before JCL starts bearing fruit. Also the use of the seed cake as fertilizer in edible crop production raises bio-safety questions. Several publications [129,130] suggest that the phorbol esters in the JCL oil would promote skin tumor. On the other hand Lin et al. [131] and Luo et al. [132] showed anti-tumor effects of the curcin from JCL oil. Furthermore, Gressel [128] warns for a serious lack of information about the effects of burning JCL oil in closed quarters, which is an important human health issue as the oil is proposed as a cooking fuel as well as a feedstock for bio-diesel production. He also calls for precaution in the use of accessions with high initial phorbol ester content since available extraction procedures for the removal of the phorbol esters are insufficient to bring those accessions to acceptable toxicological level [128].

Since very limited information is available regarding acidification, eutrophication and other unmentioned LCA impact categories of the JCL production cycle, no statements or prognoses are made concerning these issues. Increased investigation of the cultivation step of the production of JCL bio-diesel will enable researchers to assess the specific contribution of JCL in these impacts as well.

8. Conclusions

In general we can state that the inclusion of data from reports and conference proceedings compensates the lack of peer-reviewed data. This state-of-the-art literature review on the production and use of JCL, however, detects several knowledge gaps which need to be bridged before more large scale cultivation can be undertaken.

The main knowledge gaps are situated in the cultivation of the crop, for both a description of best practice as for describing the potential environmental risks or benefits.. From selection of basic plant material up to yield there are many options, with a lot of variation in available data and not enough information for optimization. For project coordinators or investors it is almost impossible to lay out a coherent and realistic business plan because almost every step in the cultivation stage is uncertain, foremost the yield.

It is obvious that the JCL system cannot meet all expectations, which have been attributed to JCL since it has been hyped, at the same time or place. The plant cannot perform all its functions together at the best level. In popular press the JCL functions are presented separately and are, without evidence, attributed to all provenances. In an agricultural system there are trade-offs between the different functions the system or the crop can serve, this is not different for JCL.

Based on the available information it is still difficult to conclude if JCL bio-diesel will meet the two essential minimum requirements for bio-fuels to be a more sustainable alternative for fossil fuels (i.e. (*i*) produced from renewable raw material and (*ii*) their use has a lower negative environmental impact). JCL is expected to be renewable, but it is not clear at which cost. The impact on the soil seems to be positive, depending on used practice and used soil types, but this contribution to soil restoration might find trade-offs in biodiversity loss. The environmental impacts discussed are lower than the fossil alternative as long as no (semi-) natural ecosystems are removed in favor of JCL and as long as the by-products of the bio-diesel production system are efficiently used. The human health issue, on the other hand, is a persistent problem which can not be neglected. The authors call for precaution and science to be applied. The booming interest at the moment and the current lack of knowledge can not support the present popularity of JCL and as such can drive unsustainable practice and this could in its turn hamper the exploration of the true JCL potential risks and benefits.

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Appendix

Appendix 1 – Collection of published JCL dry seed yields

Reference	**Location**	**AAR**[a]	**Age**	**kg tree^{-1} yr^{-1}**	**kg ha^{-1} yr^{-1}**
[13]	Nicaragua, Managua	1200	2		2327
	Nicaragua, Managua	1200	3		2786
	Nicaragua	1200	4		3484
[9]	Cape Verde	600	-	0.80	
	India		3		1733
	Nicaragua, Managua	1200	-		5000
	Mali	1020	-		2640
	Thailiand	1470	-		2146
	Mali	1020	-		8000
	Madagascar	1370	-	3.25	
	Paraguay	1370	3		100
	Paraguay	1370	4		700
	Paraguay	1370	5		1000
	Paraguay	1370	6		2000
	Paraguay	1370	7		3000
	Paraguay	1370	8		4000
	Paraguay	1370	9		4000
	Cape Verde	220	-		1750
	Cape Verde	220	-		500
	Thailand	1470	1	0.32	794
	Thailand	1470	1	0.06	
	Burkina faso	815	-	0.96	
	semi arid areas	-	-		2500
[52]	Nicaragua	1200	5	4.50	5000
[65]	Mali	1020	-		3000
[10]	-	-	-		400-12000
	Mali	1020	-		2500-3500
[8]					5000
[1]	Indian wasteland		-		2500
[60]	-		-		700-1000
[64]	Nicaragua	1200	-	4.50	5000
	India		-	3.05	6700
[28]	India	-	-		5000
[56]	India	450	1.25	1.73	1733
Pers. Comm. Kumar 2005	India, Rajasthan	610	2.5	0.47	1172
	India, Rajasthan	610	2.5	0.13	313
Pers. Comm. Buismans 2005	Mali, Digini	1020	2	0.30	337
[46]	Zimbabwe	725	-	0.4	

[a]: AAR: Average Annual Rainfall (if not reported in publication, obtained from http://www.worldclimate.com)

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Fig. captions

Fig. 1. Inputs and outputs of the *Jatropha* cultivation unit process.

Fig. 2. Dry seed yield in relation with average annual rainfall (mm) and age of the JCL crop. The plotted points represent a mix of provenances, site conditions and plant age or average annual rainfall respectively.

Sources: [9,11,13,52,53,56] and personal communication Kumar 2005 and Buisman 2005.

Fig. 3. Average shell:kernel ratio of JCL seed and standard deviation based on 21 reported data sets.

Sources: [9,10,13,26,28,30,31,59,60]

Fig. 4. Average kernel and shell composition and standard deviation based on *n* reported data sets. ◆ - minimum; ◇ - maximum.

[*] Calculated from values obtained for fat free samples since high fat content interferes with the analyses.

Sources: [9,10,13,27,30,31,55,59,60]

Fig. 5. Inputs and outputs of the *Jatropha* oil extraction unit process.

Fig. 6. Fatty Acid composition (%). C16:0 = Palmitic Acid; C18:0 = Strearic Acid; C18:1 Oleic Acid; C18:2 = Linoleic Acid. Other Acids containing Capric Acid, Myristic Acid (C14:0), Palmitoleic Acid (C16:1), Linolenic Acid (C18:3), Arachidic Acid (C20:0),

Behenic Acid (C22:0), cis-11-Eicosenoic Acid (C20:1) and cis-11,14-Eicosadienoic Acid (C20:2). n = number of observations used.

Sources: [1,13,26,56,71,75,77-79,82]

Fig. 7. Average kernel cake composition and standard deviation based on *n* reported data sets of solvent extracted JCL kernels. ◆ - minimum; ◇ - maximum. Inset table: ranges of reported chemical composition indicating the percentages of N, P, K, Ca and Mg (based on n=5 data sets).

Sources: [5,6,8,10,26,28,31,59,71,90]

Fig. 8. Inputs and outputs of the transesterification unit process

Fig. 9. Primary energy input for the production of 1000 MJ JME after pro-rata allocation of the total energy requirement of the whole production process over the JME product and the by-products based on the energy content of the JME product and the by-products. *Sources*: [64] with low cultivation intensity and [119] with high cultivation intensity. Comparison with reference systems rapeseed methyl ester (RME) and ultra low sulphur diesel (ULSD) from crude oil [111].

Figures

Fig 1.

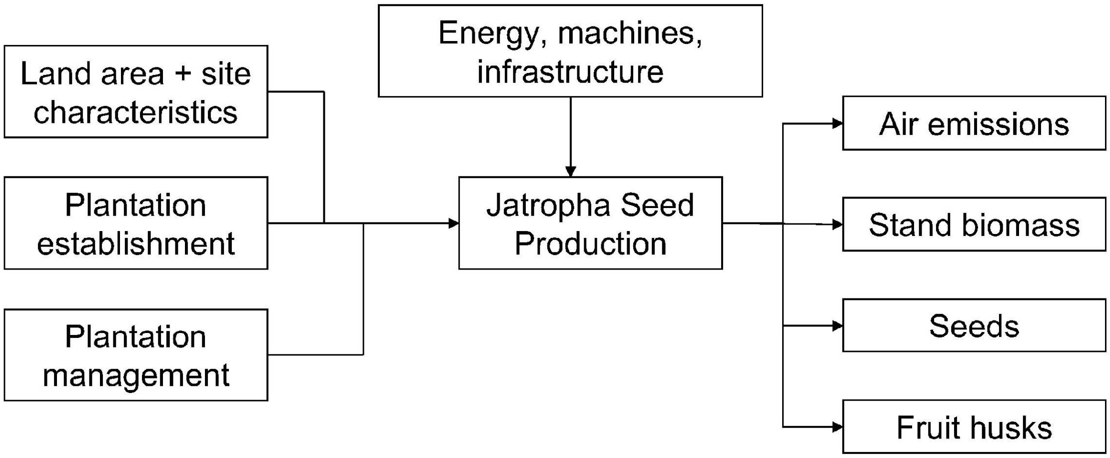
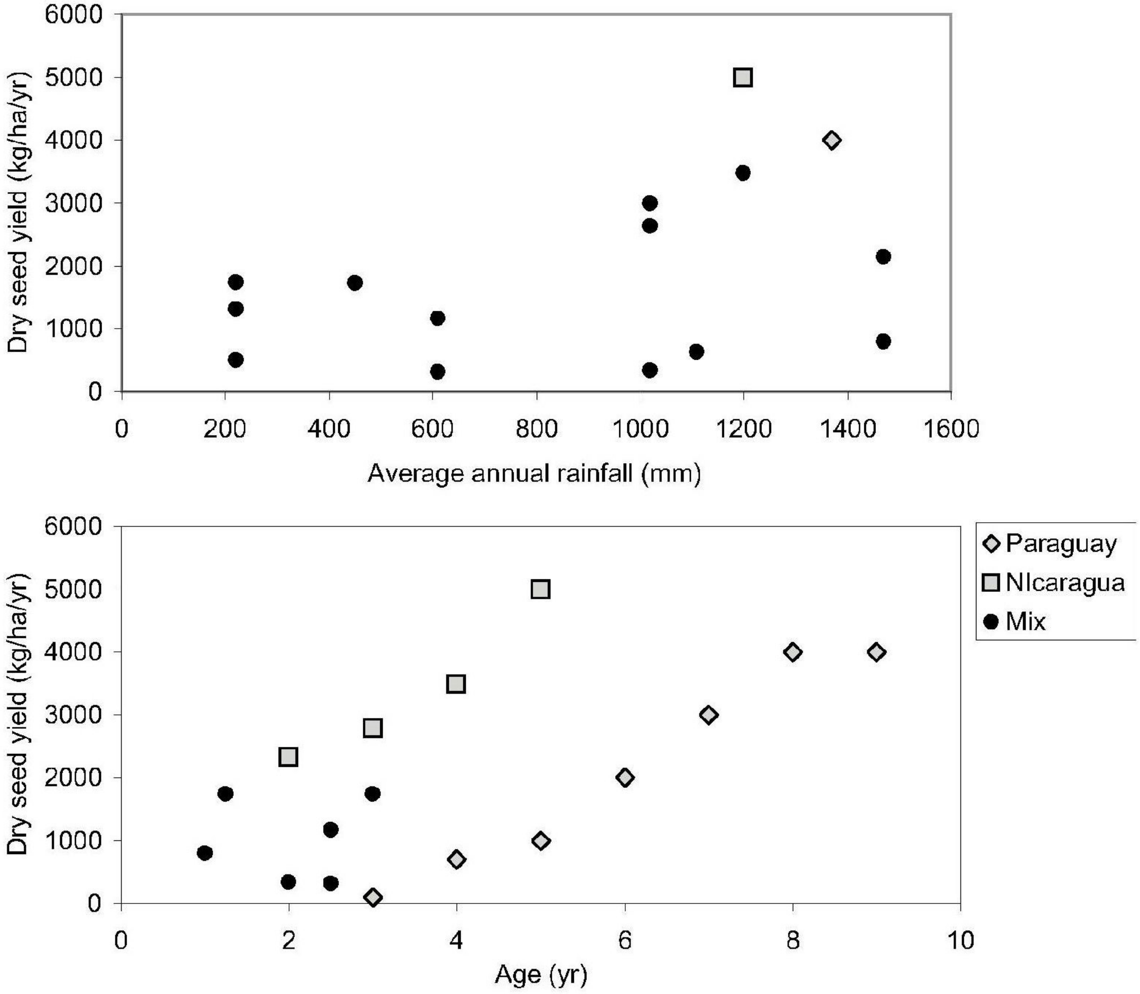
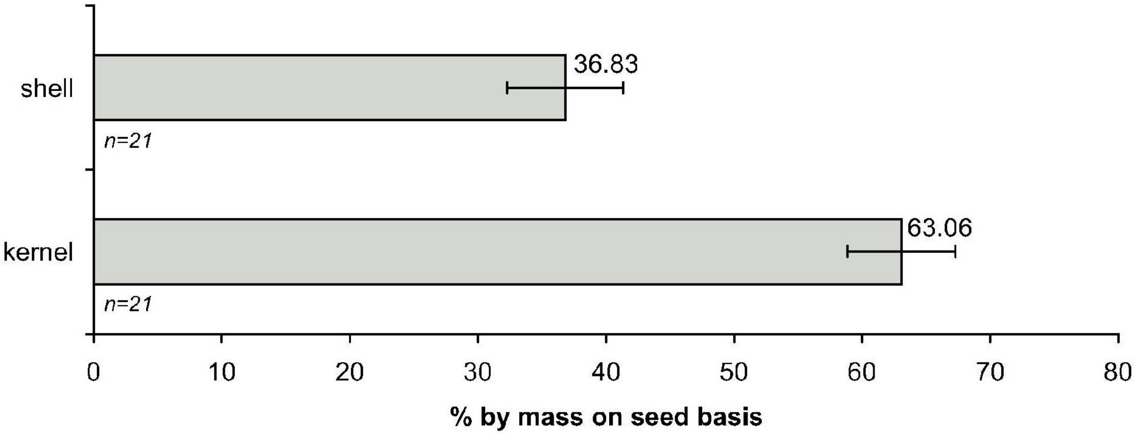


Fig 2.

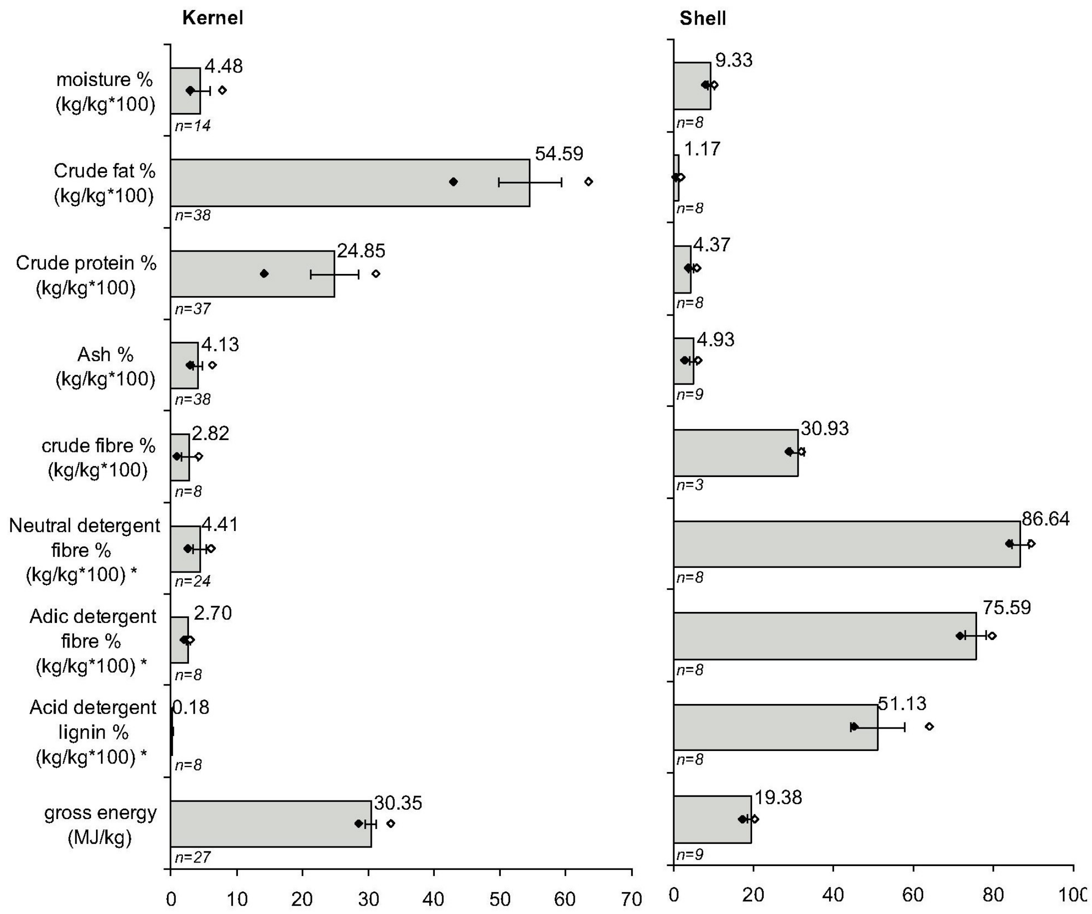


Dry seed yield (kg/ha/yr)
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
1400
1600
Average annual rainfall (mm)
Dry seed yield (kg/ha/yr)
6000
5000
4000
3000
2000
1000
0
0
2
4
6
8
10
Age (yr)
◇ Paraguay
□ NIcaragua
● Mix

Fig 3.


shell
36.83
n=21
kernel
63.06
n=21
0
10
20
30
40
50
60
70
80
% by mass on seed basis

1351 Fig 4.



1352

Fig 5.

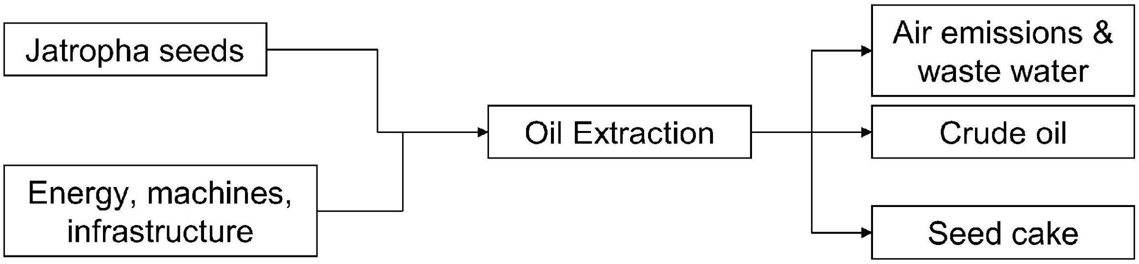
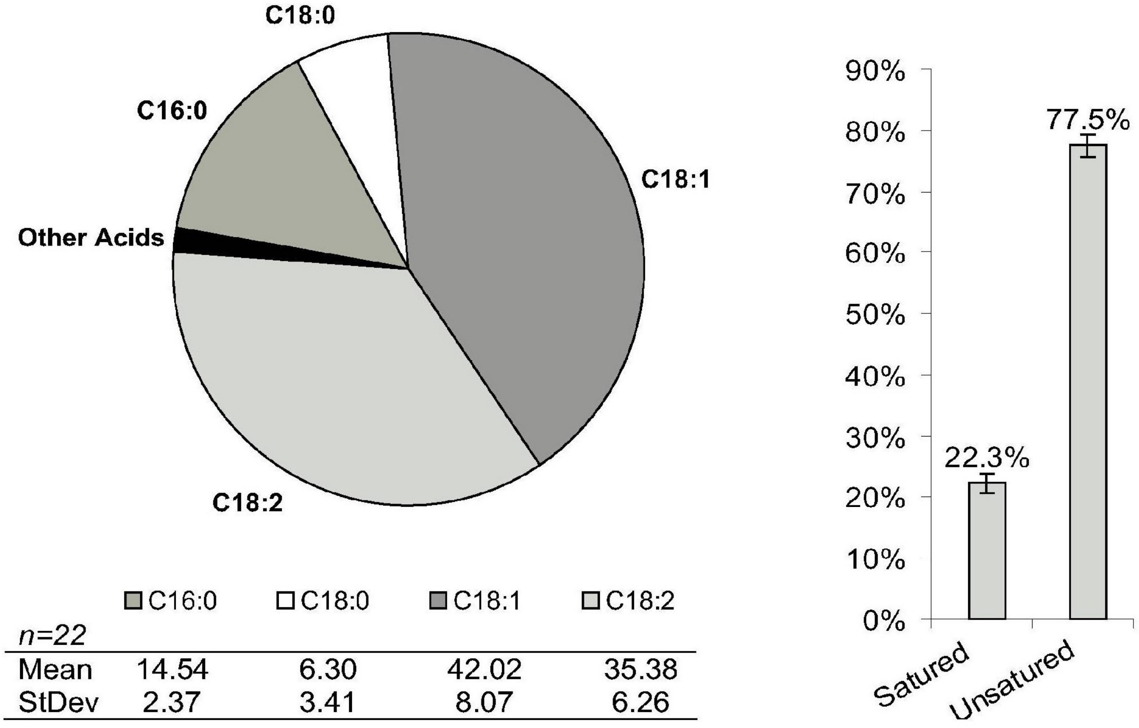
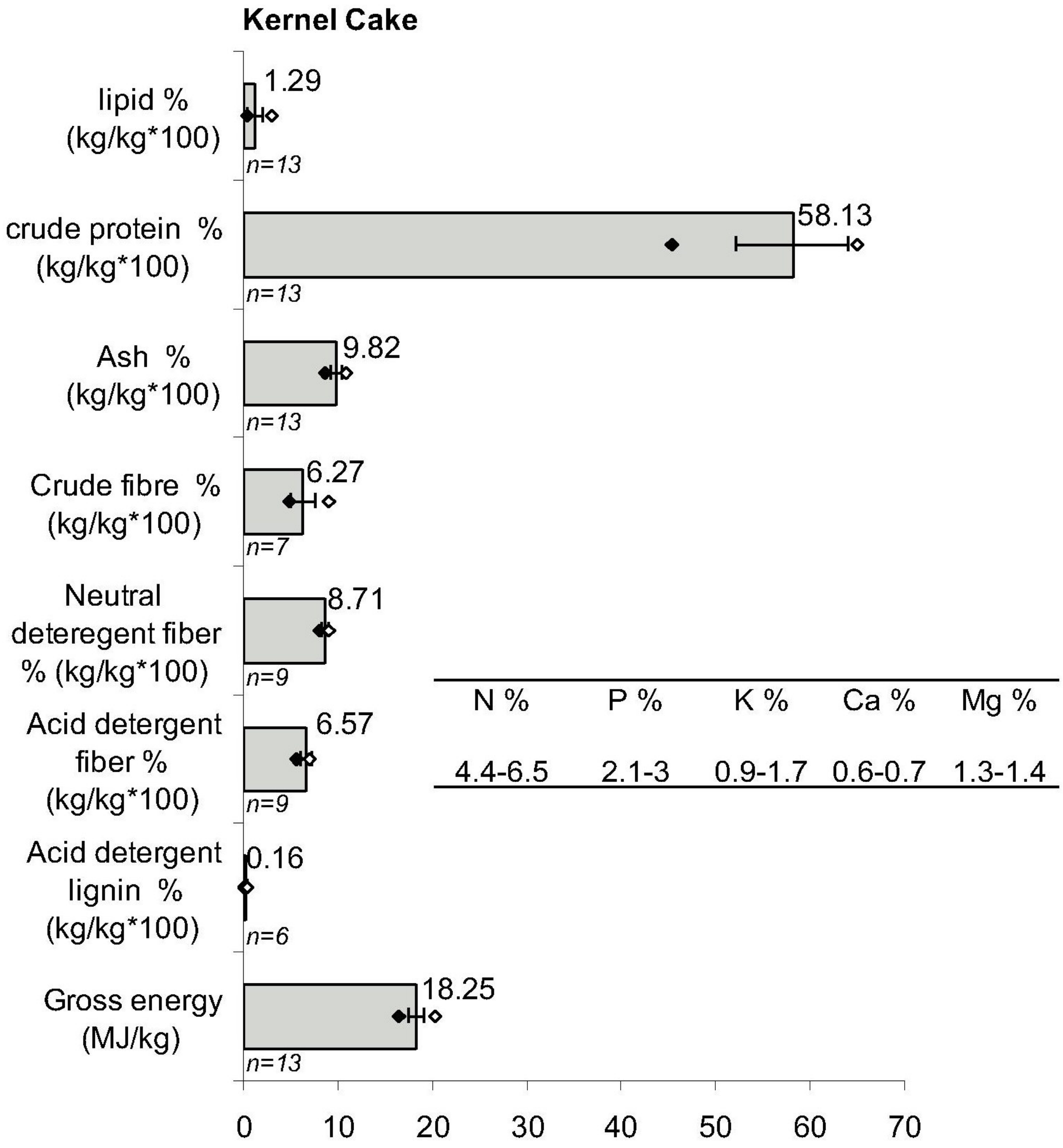

Jatropha seeds
Energy, machines, infrastructure
Oil Extraction
Air emissions & waste water
Crude oil
Seed cake

Fig 6.



n=22	C16:0	C18:0	C18:1	C18:2
Mean	14.54	6.30	42.02	35.38
StDev	2.37	3.41	8.07	6.26

Fig 7



N %	P %	K %	Ca %	Mg %
4.4-6.5	2.1-3	0.9-1.7	0.6-0.7	1.3-1.4

Fig 8

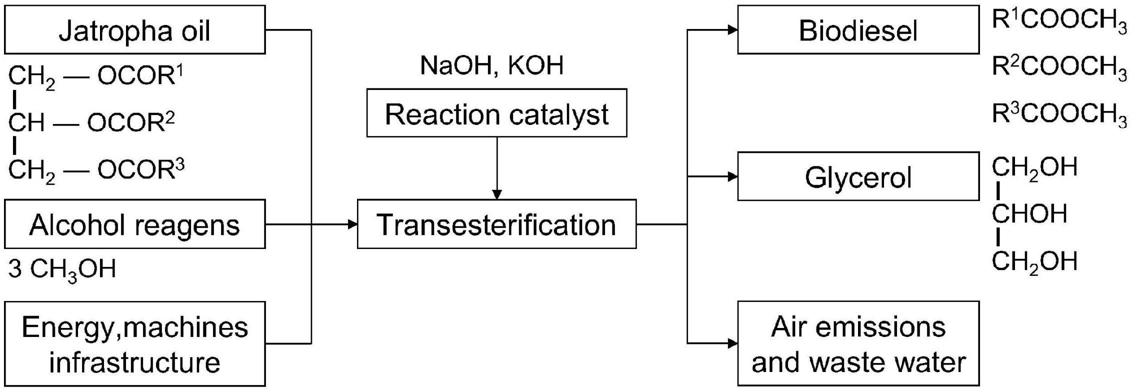
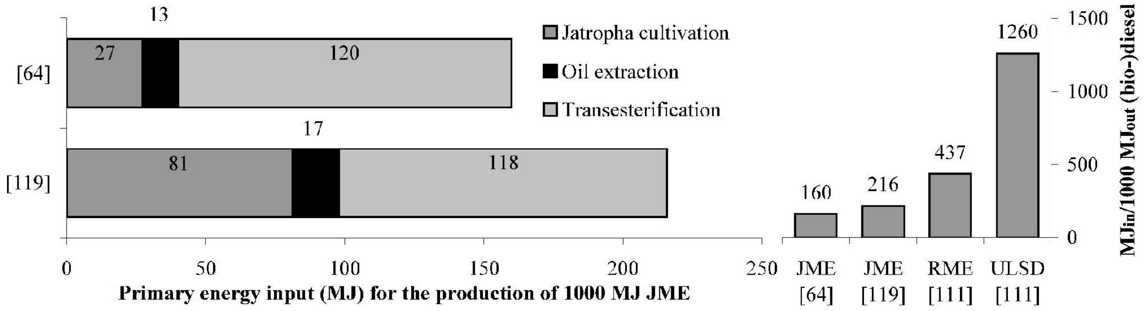

Jatropha oil
$CH_2 — OCOR^1$
$CH — OCOR^2$
$CH_2 — OCOR^3$
Alcohol reagens
$3\ CH_3OH$
Energy,machines infrastructure
NaOH, KOH
Reaction catalyst
Transesterification
Biodiesel
R^1COOCH_3
R^2COOCH_3
R^3COOCH_3
Glycerol
CH_2OH
$CHOH$
CH_2OH
Air emissions and waste water

Fig 9.



13
27
120
[64]
17
81
118
[119]
Jatropha cultivation
Oil extraction
Transesterification
0
50
100
150
200
250
Primary energy input (MJ) for the production of 1000 MJ JME
160
216
437
1260
JME [64]
JME [119]
RME [111]
ULSD [111]
0
500
1000
1500
MJin/1000 MJout (bio-)diesel

Tables

Table 1
Calculated oil yields (% of contained oil) of mechanical extraction methods

Press	Reference	Oil yield (%)
Engine driven screw press	[67]	68.0
	[6]	80.0
	[68]	79.0
Ram press	[63]	62.5
	[6]	62.5

Table 2

Reported oil yields (% of contained oil) for different chemical extraction methods and different reaction parameters

Extraction Method	Reference	Reaction temperature (°C)	Reaction pH	Time consumption (hours)	Oil yield (%)
n-hexane oil extraction (Soxhelt apparatus)	[5,9,63]	-	-	24	95-99
1st Acetone 2nd *n*-hexane	[71]	-	-	48	
Aqueous Oil Extraction (AOE)	[69]	-	-	2	38
	[70]	50	9	6	38
AOE with 10 minutes of ultrasonication as pretreatment	[70]	50	9	6	67
Aqueous Enzymatic Oil Extraction (AEOE) (hemicellulase or cellulase)	[69]	60	4.5	2	73
AEOE (alkaline protease)	[69]	60	7	2	86
	[70]	50	9	6	64
AEOE (alkaline protease) with 5 minutes of ultrasonication as pretreatment	[70]	50	9	6	74
Three phase partitioning	[72]	25	9	2	97

Table 3
JCL oil composition and characteristics.

	Range	Mean	SD	*n*
Specific gravity (g/cm³)	0.860 – 0.933	0.914	0.018	*13*
Calorific value (MJ/kg)	37.83 – 42.05	39.63	1.52	*9*
Pour point (°C)	–3			*2*
Cloud point (°C)	2			*1*
Flash point (°C)	210 – 240	235	11	*7*
Cetane value	38.0 – 51.0	46.3	6.2	*4*
Saponification number (mg/g)	102.9 – 209.0	182.8	34.3	*8*
Viscosity at 30°C (cSt)	37.00 – 54.80	46.82	7.24	*7*
Free fatty acids % (kg/kg*100)	0.18 – 3.40	2.18	1.46	*4*
Unsaponifiable % (kg/kg*100)	0.79 – 3.80	2.03	1.57	*5*
Iodine number (mg iodine/g)	92 – 112	101	7	*8*
Acid number (mg KOH/g)	0.92 – 6.16	3.71	2.17	*4*
monoglycerides % (kg/kg*100)	nd – 1.7			*1*
Diglycerides % (kg/kg*100)	2.50 – 2.70			*2*
Triglycerides % (kg/kg*100)	88.20 – 97.30			*2*
Carbon residue % (kg/kg*100)	0.07 – 0.64	0.38	0.29	*3*
Sulfur content % (kg/kg*100)	0 – 0.13			*2*

SD = standard deviation; n = number of observations used; nd = no data.
Sources: [5,13,63,71,75-85]

Table 4
Summary of case studies using JCL seed cake as fertilizer.

Reference	Country	Crop	Dosage[a]	Comments
[92]	Mali	Pearl millet	5 t ha^{-1}	46% yield increase in comparison to zero-input
[93]	Zimbabwe	Cabbage	2.5 – 10 t ha^{-1}	• 40 – 113 % yield increase in comparison to zero-input • free from pest and disease, while cutworm infestation occurred with cow manure application
[9]	Nepal	Rice	10 t ha^{-1}	11% yield increase in comparison to zero-input
[94]	India	JCL	0.75-3 t ha^{-1}	13 – 120 % yield increase in comparison to zero-input

[a]: 1 ton seed cake is produced on 0.27-0.54 ha JCL plantation. (own calculation based on an expected seed yield of 2.5 – 5 t dry seed/ha/year with an oil content of 34.4 wt% and a mechanical extraction efficiency of 75%).

Table 5
JCL (m)ethyl ester composition and characteristics with the corresponding values of the European (EN 14214:2003), German (DIN V 51606) and the USA Standards (ASTM D 6751).

	JME				**JEE**	**EN 14214:2003**	**DIN V 51606**	**ASTM D6751**
	Range	**Mean**	**SD**	***n***	***n=1***			
Density (g/cm^3)	0.864 – 0.880	0.875	0.007	*6*	0.89	0.86 - 0.90	0.87-0.90	
Calorific value (MJ/kg)	38.45 – 41.00	39.65	1.28	*3*				
Flash point (°C)	170 – 192	186	11	*4*	190	min 120	min 110	min 130
Cetane value	50.0 – 56.1	52.3	2.3	*5*	59	min 51	min 49	min 47
Saponification number (mg/g)	202.6			*1*				
Viscosity at 30°C (cSt)	4.84 – 5.65	5.11	0.47	*3*	5.54	3.5-5.0[a]	3.5-5.0[a]	1.9-6.0[a]
Iodine number (mg iodine/g)	93 – 106			*2*		max 120	max 115	max 115
Acid number (mg KOH/g)	0.06 – 0.5	0.27	0.22	*3*	0.08	max 0.5	max 0.5	max 0.5
Monoglycerides % (kg/kg*100)	0.24			*1*	0.55	max 0.8	max 0.8	
Diglycerides % (kg/kg*100)	0.07			*1*	0.19	max 0.2	max 0.4	
Triglycerides % (kg/kg*100)	nd			*0*	nd	max 0.2	max 0.4	
Carbon residue % (kg/kg*100)	0.02 – 0.50	0.18	0.27	*3*		max 0.3	max 0.3	max 0.05
Sulfur content % (kg/kg*100)	0.0036			*1*		max 0.01	max 0.01	max 0.015[b]
Sulfated ash % (kg/kg*100)	0.005 – 0.010	0.013	0.002	*4*		max 0.02	max 0.03	max 0.02
Methyl ester content % (kg/kg*100)	99.6			*1*	99.3	min 96.5		
Methanol % (kg/kg*100)	0.06 – 0.09			*2*	0.05	max 0.2	max 0.3	
Water % (kg/kg*100)	0.07 – 0.10			*1*	0.16	max 0.5	max 0.3	max 0.5
Free glycerol % (kg/kg*100)	0.015 – 0.030			*2*	nd	max 0.02	max 0.02	max 0.02
Total glycerol % (kg/kg*100)	0.088 – 0.100			*2*	0.17	max 0.25	max 0.25	max 0.24

SD = standard deviation; n = number of observations used; nd = no data. *Sources*: [5,13,63,71,75-85]

[a] The standards include viscosity in mm^2/s at 40°C. Francis et al. [8] reported a value of 4.2 mm^2/s at 40°C for JME.

[b] maximum 0.015% for S 15 Grade and maximum 0.05% for S 500 Grade

Table 6
Summary of reported alternative transesterification procedures

Conversion Method	Reference	Maximal conversion	Catalyst % (kg/kg*100)	Temp. (°C)	Time (min.)	Alcohol:oil molar ratio
Transesterification using a solid super base catalyst	[100]	93 %	1.5	70	150	methanol:oil 9:1
In-situ transesterification (skipping the oil extraction step)	[101]	87 %	1.0	60	60	100 ml (m)ethanol for 20 g whole seeds
Transesterification in supercritical alcohols	[102]	95-99 %	0	200-250	40	Supercritical (m)ethanol:oil 50:1
Bio-diesel synthesized enzymatically in presence of supercritical CO_2	[102]	60-70 %	0	45	480	(m)ethanol:oil 5:1