PREPRINT OF A PUBLISHED ARTICLE

* This is a preprint of an article published in Achten WMJ, Mathijs E, Verchot L, Singh VP, Aerts R, Muys B 2007. *Jatropha* biodiesel fueling sustainability?. Biofuels, Bioproducts and Biorefining 1(4), 283-291.

DOI: 10.1002/bbb.39

Authors: Wouter MJ Achten[a], Erik Mathijs[b], Louis Verchot[c], Virendra P Singh[d], Raf Aerts[a] and Bart Muys[a,*]

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

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

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

[d] 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)

* John Wiley & Sons, Ltd and the Society of Chemical Industry grant back to the authors The right to share with colleagues print or electronic “preprints” of the unpublished Contribution, in form and content as accepted by John Wiley & Sons, Ltd for publication in Biofuels, Bioproducts and Biorefining. Such preprints may be posted as electronic files on the Authors’ own website for personal or professional use, or on the Authors’ internal university or corporate networks/intranet, or secure external website at the Authors’ institution, but not for commercial sale or for any systematic external distribution by a third party (eg: a listserver or database connected to a public access server).

Creative Commons Attribution-Noncommercial-Share Alike 2.0 Belgium License
Permissions beyond the scope of this license may be available at

http://www3.interscience.wiley.com/journal/114071350/home/ForAuthors.html

Title:

Jatropha bio-diesel fueling sustainability?

Authors:

Wouter MJ Achten[a], Erik Mathijs[b], Louis Verchot[c], Virendra P Singh[d], Raf Aerts[a] and Bart Muys[a,*]

Affiliations:

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

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

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

[d] 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:

Prof. dr. ir. Bart Muys: Phone: +32 (0) 16 329726; Fax: +32 (0) 16 329760;

E-mail address: bart.muys@biw.kuleuven.be

ABSTRACT (250 words)

Jatropha curcas is a multipurpose, drought resistant, bio-fuel tree originating from Central and South America, but now growing pantropic. The tree produces seeds containing 27-40% inedible oil, which is easily convertible into bio-diesel. Although even some basic agronomic characteristics of *J. curcas* are not yet fully understood, the plant enjoys a booming interest, which may hold the risk of unsustainable practice. Our qualitative sustainability assessment, focusing on environmental impacts and strengthened by some socio-economic issues, is quite favorable as long as only wastelands or degraded grounds are taken into *J. curcas* cultivation. Preliminary life cycle energy and GHG balances are positive, but the GHG balance is expected to be much dependent on the type of land use which is converted to *J. curcas*. Removing natural forest will have a severe impact on the global warming potential of the *Jatropha* bio-diesel. The cultivation intensity and the distance to markets is expected to have a significant impact on the GHG balance as well. Similar reasoning applies for the impact on soil, water, vegetation structure and biodiversity, although the latter will always depend on local circumstances. Next to bio-diesel production and wasteland reclamation, *J. curcas* also hosts socio-economic development potential. The multipurpose character of the plant and the labour intensive production chain are thought to be the main drivers for rural development, but are uncertain. Environmental, economic and social sustainability dimensions interact and cannot be seen separate. In order to achieve best results with respect to both environmental as socio-economic issues, decisions have to be based on local environmental, economical, cultural and social characteristics.

Keywords: *Jatropha curcas*; bio-diesel; environmental impact; land use impact; human health; socio-economic

1 INTRODUCTION

Jatropha curcas L. (Euphorbiaceae) receives a lot of attention as a source of renewable energy. The plant has its native distributional range in Mexico, Mesoamerica, Brazil, Bolivia, Peru, Argentina and Paraguay, but is now growing pantropic.[1] As stress-tolerant ruderal the drought resistant, oil bearing small tree is well adapted to tropical semi-arid regions and marginal sites, although good environmental conditions show better crop performances (own analysis of reported environmental conditions and production rates). *J. curcas* is easily propagated and can establish quickly in a wide variety of soils, but the plant suffers immediately from frost and waterlogging.[2] The *J. curcas* seeds contain 27-40% (own calculations based on 38 reported datasets) inedible oil which can be easily converted to bio-diesel that meets the American and European standards.[3] The bio-diesel production chain also results in some valuable by-products (e.g. seedcake, fruit husks, glycerin) (fig. 1). These general characteristics and potentials of *J. curcas* result in a booming interest, which may hold the risk of unsustainable practice. The aim of this paper is to make a qualitative but critical analysis of the expected sustainability of bio-diesel production from *J. curcas*, with the main focus on the environmental sustainability, using a life cycle approach. Since sustainability knows different dimensions which cannot be seen separate, we also touch some basic socio-economic issues in a qualitative way.

Insert figure 1

2 ENVIRONMENTAL IMPACT

To address the environmental sustainability dimension we use a life cycle approach. Life cycle assessment (LCA) has shown to be an appropriate tool to measure impacts and analyze the sustainability of a production chain.[4,5] In LCA, impacts are calculated based on the comparison between the system of interest and a reference system. For a bio-diesel production system the reference system is the fossil based system that produces an equal amount of energy and (by-)products. In the following the most relevant LCA impact categories are discussed.

2.1 Energy balance

In the energy impact category, the total life cycle energy input and output is accounted for. The first limited LCA case studies[6,7] on bio-diesel production from *J. curcas* show a positive energy balance after allocating the energy input to the different products (end-product and by-products). The LCA of the system using intensive cultivation, applying fertilizer and irrigation[7], resulted in a less positive energy balance compared to the study investigating the system using low input cultivation[6]. This means that in the case study where *J. curcas* was cultivated intensively this extra energy investment in the application and production of irrigation and fertilizer did not completely pay off in an extra energy production in the form of bio-diesel. The outcome of these case studies has to be seen in the light of the present knowledge gaps in the cultivation of *J. curcas*. It is still a wild plant which shows high variability in growth and yield parameters.[8]

Insufficient systematic selection of good genetic material for different agro-climatic situations has been done, certainly for the marginal conditions for which *J. curcas* is hyped as future's hope. Furthermore there is a lack of data on growth, water use and nutrient cycling, which makes it impossible to determine the optimal management practices. Such optimization is necessary to improve/optimize the energy balance.

At present mechanical oil extraction is the most common practice and is the least contributing production step in the energy requirement of the production chain (± 8% of total life cycle energy requirement according to the available studies[7,6]). Considering the scale of the oil production at present, mechanical oil extraction is seen as the best practice. Solvent extraction is energy intensive and as such only economical in large-scale production systems.

Both available studies[6,7] show that the transesterification is the biggest contributor to the energy requirement of the final bio-diesel product (i.e. after allocation). This shows that the use of the pure *J. curcas* oil would significantly improve the energy balance. Although the use of pure plant oil is less energy efficient[9] and still brings up some engine problems,[10] it shows some opportunities for local use. In general, older diesel engines running at constant speed, often used in the agricultural sector, have fewer problems with pure plant oil, which opens up possibilities for irrigation pumps and generators in countries in the South. In case of using such engines, the lower energy efficiency of the pure oil compared with the transesterified oil will probably be of no significance.

Transportation consumes energy throughout the whole production chain. In case of strong centralization of the bio-diesel processing units (oil extraction and transesterification); this consumption might be considerable. More important will be the choice to use the end product locally or to export it to remote markets. Transporting the *J. curcas* bio-diesel from the tropical regions to European or American markets will make the energy balance less positive (in the study of Tobin and Fulford[5] the positive energy effect was reduced with 8%). Exporting the *J. curcas* seeds or oil to be processed near those remote markets is expected to have a higher impact.

In the studies mentioned before, allocations were made to the energetic content of the by-products (e.g. seed cake and glycerin). This allocation made the calculated energy balances much more positive. In reality the balance will only be positive if the accounted by-products are used efficiently. Seedcake can be used as bio-fertilizer, but it can also be used as feedstock for biogas production before using it as soil amendment. The effluent of the digester is still very valuable to substitute chemical fertilizer. After detoxification the seed cake is suitable as protein rich animal feed as well.[8] In case that the detoxification becomes viable, using the cake as fodder is believed to considerably improve the energy balance of the system. The glycerin can be burned or substitute for the fossil based production of the glycerin used in the cosmetic industry. Using other by-products will again improve the energy balance. The fruit husks can be fermented as well, but have shown to be a successful feedstock for gasification, achieving similar results as wood.[11] Furthermore there is the pruned wood which can produce heat. There is wood from annual pruning and wood from coppicing the total aboveground biomass every 10 years. The feasibility (economically, environmental, infrastructural) of using these by-products efficiently in practice is still under debate and is much dependant on the organization of the production system and local traditional practice and potential.

2.2 Global warming potential

The global warming impact category refers to the impact the production and use of a product has on global warming compared to the reference system. Both aforementioned limited LCA case studies showed lower impacts for the bio-diesel system in comparison to fossil diesel. Although 90% of the life cycle greenhouse gas (GHG) emissions are a result of the end use (fig. 1) of the bio-diesel[7] it is interesting to discuss the most important contributing steps of the production phase.

In accordance with the energy requirement, the cultivation and transesterification steps are important potential contributors. Applying fertilizer and irrigation causes considerable GHG emissions. The production of fertilizer is GHG intensive, but the importance of the air emission, such as N_2O, caused by the addition of nitrogen to agricultural systems in the form of synthetic fertilizer may not be underestimated.[12,13] Again, further investigation into the optimization of inputs is necessary in order to reach an optimized GHG balance. The same applies for the transesterification. Adding this chemical conversion causes substantial amounts of additional GHG emissions. With respect to transportation and efficiently using the by-products, the same reasoning as with the energy balance applies.

For the impact on the global warming potential of *J. curcas* in comparison to a fossil based diesel production system, we also have to account the GHG emissions caused by the land use change from the original land use to *J. curcas* cultivation. This source of GHG emissions is not included in previous cited LCA case studies. The amount of GHG emissions caused by land use change is much dependant on the kind of the original land use which is removed in favor of *J. curcas*. The average carbon stock of the *J. curcas* biomass stand then has to be compared with the average stock of the base line scenario, which is the mix of original land use. Replacement of natural dryland forest would for example cause a significant GHG emission that may not get compensated by the carbon offset in the new plantation.[14] Since yields are rather unpredictable, both on good as on bad sites, allocating wasteland to *J. curcas* can be seen as the lowest risk option at the moment. Removing the present vegetation from wasteland sites will in most cases not cause high GHG emissions. For conversion of forest land, this will not be the case. The carbon sequestration rate of *J. curcas* (± 2.25 tons CO_2 sequestration in the standing biomass, excluding the seeds, ha^{-1} yr^{-1})[8] will probably be higher than wasteland vegetation as well. Such higher rate will again lower the global warming impact of the system. Furthermore the land use change will have its impact on the soil carbon as well. Although this is difficult to prospect it can be expected (see the impact on soil in section 2.3.2) that in case of wasteland reclamation the *J. curcas* system, including the use of the seed cake as soil amendment, will increase the carbon sequestration in the soil, while for conversion of forest land, soil carbon mineralization would cause GHG emissions.

2.3 Land use impact

In this category, the impact of the new land use is assessed in comparison to the impact of the baseline scenario, which is the mix of the former land use in the considered plantation area. In order to express such impacts independent from the local site conditions, both impacts have to be calculated in relation to a predefined reference system (e.g., the potential natural vegetation of the site). In such an assessment, we may look at the impact on the ecosystem structure and functioning.[15]

Since the amount of occupied area is an important factor of land use impact, it is clear that for this impact category the *J. curcas* cultivation will be the most important step of the whole bio-diesel production chain. Since a comparison is made with the original land use, the land use impact of introducing *J. curcas* cultivation will mainly depend on the type of land use which is removed in favour of *J. curcas*. In the following qualitative land use impact assessment we will use the two extremes to clarify our reasoning (i.e., wasteland versus natural forest). The system for *J. curcas* cultivation is an important variable as well. Three cultivation systems can be distinguished: (*i*) *J. curcas* in hedges, as living fence, for control or prevention of soil erosion (wind break, contour trenching, sediment traps); (*ii*) small scale agroforestry and block plantations and (*iii*) large scale commercial monoculture plantations.

2.3.1 Ecosystem structure

The drought tolerant character of *J. curcas* makes it possible to reclaim wastelands which are only covered with scarce vegetation. In such a situation the introduction of *J. curcas* is expected to cause an improvement of vegetation structure and biodiversity. A reverse effect is expected when a relatively undisturbed natural ecosystem (e.g. savannah woodland, miombo and mopane woodland, dryland forest) is converted to *J. curcas*. In comparison to the marginal vegetation on wastelands *J. curcas* is expected to develop a higher biomass production and a better vegetative ground cover. In such sites, the introduction of *J. curcas* can even stimulate the development of improved habitat patches which provide opportunities for the establishment of other species. The direction and strength of these possible effects on wastelands is strongly dependent on the system of cultivation. Monocultures will build up a lot of living biomass and will create a microclimate, but will not create a lot of habitat diversity. Furthermore such monocultures are often managed quite intensively as well. The application of fertilizers, irrigation, biocides and soil work will bring along negative impacts on biodiversity.[16] Hedges create more gradients and landscape connectivity, possible diversity sinks and corridors.[17] The low management need of this cultivation type is believed to cause less severe impacts. However, fertilizing, particularly in the case of wastelands, will be necessary for sustainability, to achieve higher yields and to prevent soil exhaustion, again underlining the need for quantitative research in nutrient cycles and optimization of inputs. In the case of converting wasteland, *J. curcas* seems to ensure an improvement in vegetation structure, while the impact on the biodiversity depends on the situation.

In general we have to be aware that in most situations *J. curcas* is an exotic species. Some reports conclude that *J. curcas* shows invasive characteristics.[18] In addition, the toxicity of the seed cake used as fertilizer might cause phytotoxicity expressed in a reduced germination[2] of local species. Research on the allelopathic effects of *J. curcas* on the local ecosystem is required in order to clarify these issues.

2.3.2 Ecosystem functioning

Jatropha curcas can be propagated vegetatively (cuttings) and generatively (seeds). Propagated by seed, the plant develops a remarkably predictive root structure with a taproot and four laterals (pers. obs.). When using cuttings the taproot will not form and the root system will evolve into a dense root carpet, suitable for preventing sheet erosion and for accumulating sediment, but vulnerable to landslides and uprooting by wind. The plants propagated through seeds are believed to be very suitable for erosion (water and wind) control and prevention. A lateral rooting system stabilizes the superficial soil and the strong anchoring of a taproot makes *J. curcas* extremely promising for soil stabilization.[19] The protection against erosion can be strengthened by simple management practices. Leaving the shed leaves and the weeded undergrowth as mulch and bringing back the seedcake as bio-fertilizer is believed to have a positive effect on the soil. The enrichment of organic material improves the soil structure and the water holding capacity. The cultivation of *J. curcas* for bio-diesel production is expected to have an overall positive effect on the fertility, stability and carbon storage of soils in wasteland situations. But, again, a lot will depend on the management intensity. The use of heavy machinery may cause compaction, which in turn can inhibit many positive effects. Replacing natural forest may have significant mechanical impacts on the soil at first. In such case it is reasonable to expect that substantial amounts of organic matter will get lost through decomposition, causing mainly negative impacts on GHG emissions, soil fertility, soil structure and water holding capacity.

Currently, the erosion prevention capacity of *J. curcas* has not been subject to quantitative research. *J. curcas* is a deciduous species, shedding its leaves during dry season. The leaves will only re-grow when water becomes available again. The first rains of the following rainy season are thus not buffered by the canopy. These first rain events might cause significant soil loss. The leftover mulch might be a good buffer during this period.

The use of seedcake is believed to be very positive for soil organic matter and soil structure. However, the seedcake contains toxins (phorbol esters, trypsin inhibitors, lectins, phytates), which give the cake biopesticidal/insecticidal and molluscicidal properties,[8,20] but could have an impact on microbial communities and biogeochemical cycles as well. Research on long term effects of seedcake addition to soil is necessary. Furthermore caution is necessary on the use of the seedcake as fertilizer for edible crops. Although the phorbol esters decompose completely within 6 days,[20] it is still advisable to check the absence of phorbol esters in those edible crops.

In the assessment of the impact on the water balance we have to look both at on-site effects as on off-site effects.[21] Starting from wasteland *J. curcas* will bring on-site improvement of the water balance. Through the strong increase in evapotranspiration (ET), causing a reduction of surface runoff and a higher infiltration capacity, *J. curcas* will give the system more control over the water cycle. These on-site effects might cause a more leveled flow in the rivers and streams off-site (i.e. increasing base flow, less peak flows and no flash floods). In case the ET of *J. curcas* would exceed the ET of the natural vegetation this would lead to decreasing water availability downstream. This effect has already been shown for *Eucalyptus*,[22] but still has to be investigated for *J. curcas*.

3 SOCIO-ECONOMIC POTENTIAL

The environmental side of the story is very important, but it is not the main driver of development in the South. Economic viability and social benefits are the first concerns when it comes to the implementation of a new biological production system in developing countries and thus cannot be seen separate. In fact no project can be considered sustainable if it is not economical or social sustainable.[23] Since this is a complex matter and since only little is known, we will only discuss some basic issues specific to *J. curcas* in a qualitative way.

J. curcas is a toxic plant which produces inedible oil. With respect to land use pressure there is well founded concern that expansion of *J. curcas* cultivation could displace food production in rural areas. If it is produced on lands which are not suitable for edible crop production this will, of course, not be a problem. However, if market prices for bio-diesel continue to rise, countries that wish to maintain land in food production might need to consider offering appropriate incentives to farmers not to switch to this cash crop. On the other hand the toxicity of the *J. curcas* seeds, oil and cake can hold human health problems. Since the workers are in close contact with the seeds, oil and seed cake, accidental intake cannot be fully excluded. Furthermore, some studies isolated a tumor promoting phorbol ester from the *J. curcas* oil.[24,25] We have to be aware of this health risk, since the skin of the workers comes into direct contact with the oil easily.

The cultivation, but mainly the harvesting of the *J. curcas* fruits is very labour intensive. The fruits have to be harvested at maturity. Since the fruits do not ripen all at the same time, the harvest cannot be mechanized yet. Such high labor requirement both brings along potential socio-economic benefits and risks. In areas with high legal unemployment this labor need may translate into substantial job creation. But, labour both has its economic and social costs. The presence of available jobs does not automatically improve rural livelihood. Attention has to be paid that new jobs meet national and international standards. Reported cost-benefit analyses[26,27] are variable and often do not include the full cost of labour that meets national and international standards, as they use the legal minimum wage of the country at stake. In fact, using the full cost of labour may render such analyses as unprofitable. Considering both the economic and social costs of labour in an intensive system, as *J. curcas*, together with the current market prices, knowledge gaps on the *J. curcas* system and specific social and cultural contexts the economic viability of a *J. curcas* based oil production system is uncertain. Technological innovations may improve the socio-economic viability of such initiatives in the future.

Socio-ecological strengths of *J. curcas* are that (*i*) it already grows 'naturally' in many places and (*ii*) that it is a multipurpose plant. *J. curcas* is traditionally used for medicinal purposes. In some communities the oil is used to make soap. Furthermore, the plant, which is not browsed, is used as a living fence to protect food crops, as a tool for ecological restoration in degraded areas, and as erosion control and prevention.[28,29] If, in such situations, the seeds are harvested and sold to bio-diesel producers, the result will be rural job creation and income generation. If the investment has been made for functions other than bio-diesel production, the sale of the seeds is an additional benefit. In addition to these purposes the bio-diesel production from *J. curcas* not only results in a fossil fuel substitute, but also in an array of by-products which are locally interesting.

The organization model of the production chain is believed to have an impact on the socio-economic potential as well. A distinction can be made between (*i*) large- scale, centralized estates working with outgrowers; and (*ii*) a decentralized setup.[8] Using the decentralized model is believed to increase the local availability of the bio-diesel and by-products[8] enhancing the rural development, although it is not clear that decentralized setups have the potential to take full advantage of these opportunities. This is mainly dependent on local culture and available capability and knowledge. Centralized setups, on the other hand, gain economies of scale from the income of the bio-diesel and the by-products. The contract farmers generally have an ensured market for their seeds and in many cases crop management support. Centralized estates may enhance rural development mainly through job creation, income generation and capability support, but this can only be positively acknowledged if those systems comply with national and international labour standards.

The investments needed for a decentralized initiative are smaller than in the case of a centralized setup, but in general the same applies for the shoulders which have to bear these investments. Since the annual seed yield is only roughly known and the responsiveness of the yield on inputs as fertilizers and irrigation is still badly understood, this question on economic viability is still impossible to address accurately. This risk has to be taken both by centralized as decentralized setups. Taking risks is an important part of the definition of entrepreneurial. Clearly only the better endowed farmers will be able to experiment in this upcoming agricultural production system and show the way, this also applies for both centralized as decentralized setup.

Important to mention is the double potential of *J. curcas* bio-diesel to attract carbon credits from the Clean Development Mechanism (CDM) market. *J. curcas* can be used for CDM afforestetion/reforestation projects with carbon credits for the carbon sequestration. Simultaneously these projects can serve as CDM energy project as well, which can apply for credits for the substitution of fossil fuels.

4 CONCLUSION

With the available knowledge on *J. curcas,* it is not easy to answer the title question. Concerning seed yield and yield responsiveness of inputs, there is a serious lack of workable data. *J. curcas* is still a wild plant which exhibits a lot of variability in yield, oil content and oil quality. Given the booming interest which *J. curcas* receives nowadays, there is an urgent need for better data to guide investments. Preliminary results on the life cycle energy balance and global warming potential of bio-diesel from *J. curcas* are favorable, but it is important to note that the GHG balance is tightly linked to the type of land use which is removed and the intensity of the cultivation. Impacts on vegetation structure, biodiversity, soil and water are uncertain, but are expected to be unacceptable in case of converting relatively undisturbed (semi-)natural ecosystems to *J. curcas*. In case of reclaiming wasteland and degraded grounds impacts are expected to be acceptable or even positive. Based on the uncertainty and the discussion above, we would like to be cautious and restrict public funding to *J. curcas* introduction to wastelands or degraded grounds, where environmental benefits might outweigh against potential negative impacts and where *J. curcas* can fully show its multipurpose potential (as decided in India). From a socio-economic point of view, we would recommend that initial efforts not start with immediate involvement of individual small-scale farmers and their fields. First, science and business models need to be given time to be applied. There is urgent need for systematic yield monitoring for different input regimes and for systematic selection of the best suitable genetic material. Downstream of the *J. curcas* cultivation, the authors call for the use of different models to properly fit cultural and social contexts with systematic monitoring to ensure that lessons are learned and transmitted.

Sustainability can be framed by three inseparable dimensions: environmental, economic and social.[23] Higher sustainability in one dimension does not necessarily cause higher sustainability in the other. From an environmental point of view *J. curcas* cultivation is best restricted to wasteland, but will that be economically and socially viable? Low technological setups can improve the energy balance and the global warming potential of the system, but on the other hand can imply socially unacceptable labour conditions. From a biodiversity perspective the hedge cultivation of *J. curcas* is expected to have the least negative impact, but this cultivation type is probably the least economic. Highly negative impacts in a certain dimension can cause negative impacts in another dimension or the other way around. Negative impacts on environment itself can cause negative impacts in the social dimension. Such interactions are often situation-specific and oblige us to base our decisions on the environmental, economic and social characteristics of the places at interest. Decisions on tradeoffs between the different sustainability dimensions show us that also the political and ethical side of bio-energy production cannot be ignored.

ACKNOWLEDGEMENTS

This research is funded by the Flemish Interuniversity Council – University Development Co-operation (VLIR-UDC) and the K.U.Leuven Research Fund, and is a collaboration between K.U.Leuven and the World Agroforestry Centre (ICRAF). The constructive comments provided by two anonymous referees are greatly acknowledged.

5 REFERENCES

1 USDA ARS, National Genetic Resources Program - National Germplasm Resources Laboratory. *Jatropha curcas* infromation from Germplasm Resources Information Network - (GRIN) [Online Database]. http://www.ars-grin.gov/cgi-

bin/npgs/html/taxon.pl?20692. 2000; Accessed on 2007-11-9.

2 Heller J. Physic nut. *Jatropha curcas* L. Promoting the conservation and use of underutilized and neglected crops. 1. PhD [dissertation]. Rome: Institute of Plant Genetic and Crop Plant Research, Gatersleben, Germany & International Plant Genetic Resource Institute, Rome, Italy; 1996.

3 Azam MM, Waris A and Nahar NM. Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. *Biomass & Bioenergy*. 2005;**29**(4):293-302.

4 Fredriksson H, Baky A, Bernesson S, Nordberg A, Noren O and Hansson P-A. Use of on-farm produced biofuels on organic farms - Evaluation of energy balances and environmental loads for three possible fuels. *Agricultural Systems*. 2006;**89**(1):184-203.

5 Lindeijer E, Müller-Wenk R and Steen B, Impact assessment of resources and land use, in *Life-cycle Impact Assessment: Striving towards Best Practice,* ed by Udo de Haes HA, Finnveden G, Goedkoop M, Hauschild M, Hertwich EG, Hofstetter P *et al.* Society of Environmental Toxicology and Chemistry, Pensacola, FL, pp. 11-64 (2002).

6 Tobin J and Fulford DJ. Life Cycle Assessment of the production of biodiesel from

Jatropha. MSc [dissertation]. The University of Reading; 2005.

7 Prueksakorn K and Gheewala SH. Energy and greenhouse gas implications of biodiesel production from *Jatropha curcas L.* In: Proceedings of The 2nd Joint International Conference on "Sustainable Energy and Environments (SEE 2006)"; 2006 Nov 21-23 ; Bangkok, Thailand.

8 Francis G, Edinger R and Becker K. A concept for simultaneous wasteland reclamation, fuel production, and socio-economic development in degraded areas in India: need, potential and perspectives of *Jatropha* plantations. *Natural Resources Forum*. 2005;**29**(1):12-24.

9 Prasad CMV, Krishna MVSM, Reddy CP and Mohan KR. Performance evaluation of non-edible vegetable oils as substitute fuels in low heat rejection diesel engines. *Proceedings of the Institution of Mechanical Engineers Part D - Journal of automobile engineering*. 2000;**214**(Part D):181-187.

10 Meher LC, Vidya Sagar D and Naik SN. Technical aspects of biodiesel production by transesterification - a review. *Renewable and Sustainable Energy Reviews*. 2006;**10**(3):248-268.

11 Vyas DK and Singh RN. Feasibility study of *Jatropha* seed husk as an open core gasifier feedstock. *Renewable Energy*. 2007;**32**(3):512-517.

12 Brentrup F, Kusters J, Kuhlmann H and Lammel J. Application of the life cycle assessment methodology to agricultural production: an example of sugar beet production with different forms of nitrogen fertilisers. *European Journal of Agronomy*. 2001;**14**(3): 221-233.

13 Gasol CM, Gabarrell X, Anton A, Rigola M, Carrasco J, Ciria P *et al.* Life cycle assessment of a Brassica carinata bioenergy cropping system in southern Europe. *Biomass and Bioenergy*. 2007;**31**(8): 543-555.

14 Garcia-Quijano J, Peters J, Cockx L, van Wyk G, Rosanov A, Deckmyn G *et al.* Carbon sequestration and environmental effects of afforestation with Pinus radiata D. Don in the Western Cape, South Africa. *Climatic Change*. 2007;**83**(3):323-355.

15 Wagendorp T, Gulinck H, Coppin P and Muys B. Land use impact evaluation in life cycle assessment based on ecosystem thermodynamics. *Energy*. 2006;**31**(1):112-125.

16 Van Dobben HF, Ter Braak CJF and Dirkse GM. Undergrowth as a biomonitor for deposition of nitrogen and acidity in pine forest. *Forest Ecology and Management*. 1999;**114**(1):83-95.

17 Deckers B, Verheyen K, Hermy M and Muys B. Differential environmental response of plant functional types in hedgerow habitats. *Basic and Applied Ecology*. 2004;**5**(6):551-566.

18 Vos P. Case studies on the status of invasive woody plant species in the Western Indian Ocean: 2. The Comoros Archipelago (Union of the Comoros and Mayotte). Rome, Italy: FAO; 2004. Forestry Department, Food and Agriculture Organization of the United Nations. Forest Health & Biosecurity, Working Papers FBS/4-2E. http://www.fao.org/forestry/webview/media?mediaId=6840&langId=1

19 Reubens B, Poesen J, Danjon F, Geudens G and Muys B. The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: a review. *Trees - Structure and Function*. 2007;**21**(4):385-402.

20 Rug M, Sporer F, Wink M, Liu SY, Henning R and Ruppel A. Molluscicidal properties of *J. curcas* against vector snails of the human parasites *Schistosoma mansoni* and *S. japonicum*. In: Gübitz GM, Mittelbach M, Trabi M, editors. Biofuels and industrial products from *Jatropha curcas* - Proceedings from the Symposium "Jatropha 97"; Managua, Nicaragua.

21 Heuvelmans G, Muys B and Feyen J. Extending the life cycle methodology to cover impacts of land use systems on the water balance. *International Journal of Life Cycle Assessment*. 2005;**10**(2):113-119.

22 Zomer RJ, Trabucco A, van Straaten O and Bossio DA. Carbon, land and water: A global analysis of the hydrologic dimensions of climate change mitigation through afforestation/reforestation. Colombo, Sri Lanka: International Water Management

Institute; 2006. IWMI Research Report. 101. http://www.iwmi.cgiar.org/pubs/pub101/RR101.pdf

23 Madlener R, Robledo C, Muys B and Blanco Freja JT. A sustainability framework for enhancing the long-term success of LULUCF Projects. *Climatic Change*. 2006;**75**(1-2):241-271.

24 Horiuchi T, Fujiki H, Hirota M, Suttajit M, Suganuma M, Yoshioka A *et al.* Presence of tumor promoters in the seed oil of *Jatropha curcas* L. from Thailand. *Japanese Journal of Cancer Research*. 1987;**78**(3):223-226.

25 Hirota M, Suttajit M, Suguri H, Endo Y, Shudo K, Wongchai V *et al.* A new tumor promoter from the seed oil of *Jatropha curcas* L., an intramolecular diester of 12-deoxy-16-hydroxyphorbol. *Cancer Research*. 1988; **48**(20):5800-5804.

26 Openshaw K. A review of *Jatropha curcas*: an oil plant of unfulfilled promise. *Biomass & Bioenergy*. 2000;**19** (1):1-15.

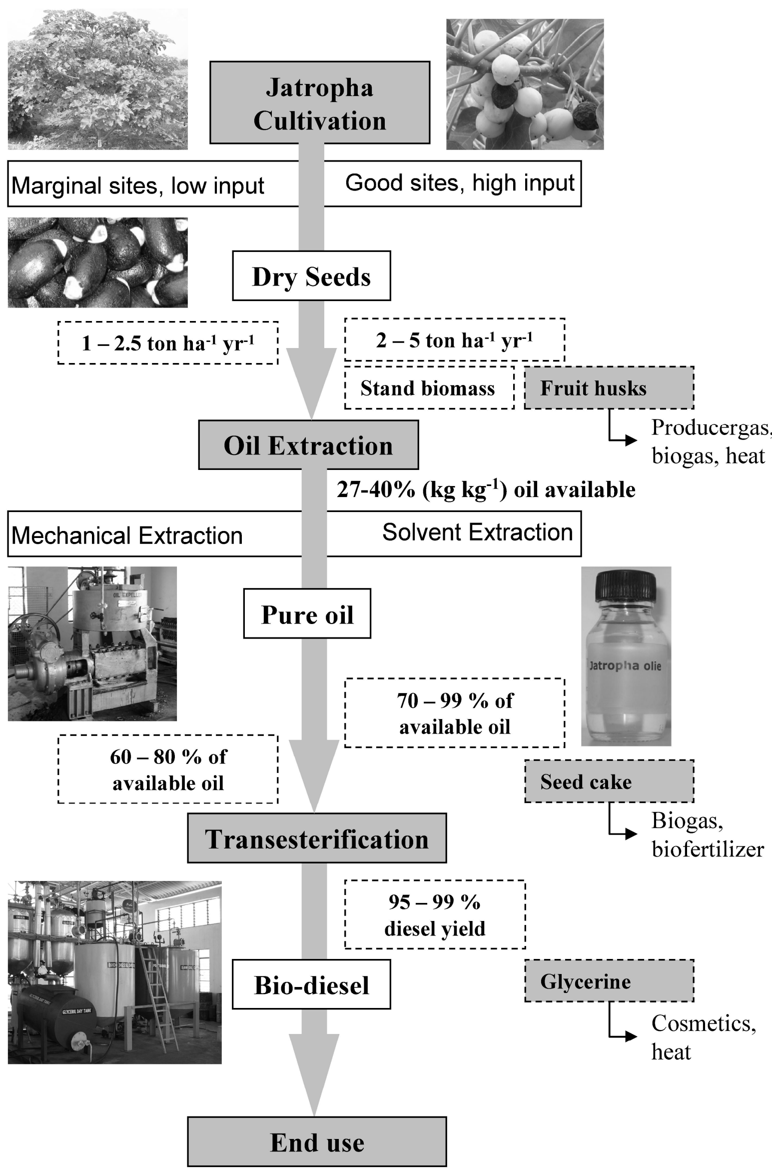
27 Henning RK. "The *Jatropha* system" - Economy & dissemination strategy. In: International conference "Renewables 2004"; Bonn, Germany.

28 Gubitz GM, Mittelbach M and Trabi M. Exploitation of the tropical oil seed plant *Jatropha curcas* L. *Bioresource Technology*. 1999; **67**(1):73-82.

29 Zahawi RA. Establishment and growth of living fence species: an overlooked tool for the restoration of degraded areas in the tropics. *Restoration Ecology*. 2005;**13**(1):92-102.

6 FIGURE CAPTIONS

Figure 1 – *J. curcas* biodiesel production chain



Top

Wouter MJ Achten – Figure 1