A review of the sustainability of Jatropha cultivation projects for biodiesel production in southern Africa: Implications for energy policy in Botswana

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Jatropha curcas L. biofuel development is considered a strategy for achieving energy security, climate change mitigation, foreign exchange savings and economic development. This paper reviews the experiences of some southern African countries with the impacts of Jatropha biofuel development on sustainability, with a view to providing lessons for biofuel development policy for Botswana. The review has shown that most of the large commercial plantations planned to produce jatropha seed for home consumption and export were not economically viable mainly due to low seed yield, high cost of production, delayed production and uncompetitive feedstock prices. On the other hand, smallholder-based jatropha biofuel projects were economically viable due to their low input costs. Analysis of social impacts showed that jatropha production has been associated with loss of rights to land, low compensation levels, and compromised food security where land and other production inputs were diverted from food crops to jatropha production. Positive social impacts in some countries included increased employment opportunities and incomes. Jatropha production is associated with environmental impacts such as loss of biodiversity, high water requirements and high carbon debts resulting from conversion of land. Positive environmental impacts included high energy return on investment and high GHG savings when Jatropha is cultivated on abandoned agricultural fields as revealed by research in some parts of West Africa. Policy considerations for the Government of Botswana include: providing support to biofuel projects at their early stage of development, discouraging large plantation business models until such time that research in Botswana produces high seed-yielding Jatropha varieties, introducing legal safeguards for protection of land rights of local communities, and ensuring that land-use change and high carbon debts are minimized as they have adverse impacts on biodiversity and climate change.

Keywords: s*outhern Africa; sustainability; jatropha projects; biodiesel production; energy policy; Botswana.*

1.0 Introduction

Biofuel development is considered to be an important strategy for energy security, climate change mitigation, foreign exchange savings, economic growth and rural development, (Gasparatos et al., 2015). Energy security is a key driver for biofuel development in countries such as USA, China and some EU member states, whereas climate change has been a major driver in the EU (Commission of the European Communities, 2009). Rural development, economic growth and energy security are key drivers of biofuel development in sub-Saharan African countries, where poverty and shortage of foreign exchange are major challenges. For instance, the key drivers of the pre-2000 biofuel projects in Kenya, Malawi, South Africa and Zimbabwe were energy security and foreign exchange savings (Dufey, 2006; Gasparatos et al., 2015; von Maltitz et al., 2016).

The potential of biofuels to achieve the above-mentioned development goals is increasingly being questioned, mainly because their production and use is associated with social, economic and environmental risks. Economic risks include high food prices and perverse effects associated with subsidies, and high opportunity costs of land use. Although the production of biofuels may not necessarily compete with food products, the inputs used in their production may compete with those for food production, and this may ultimately lead to an increase in food prices. Social risks associated with production and use of biofuels includes food insecurity, displacement of small-scale farmers and employment associated with poor health and safety (FAO, 2008). Environmental risks include biodiversity loss, climate change and degradation of ecosystem services (Searchinger et al., 2008; Gasparatos et al., 2011).

To avoid these risks, the development of biofuels needs to be guided by comprehensive national policies with legal and regulatory frameworks. As clearly articulated by Janssen and Rutz

(2012), regulatory frameworks for biofuels include legislation for the establishment of institutional structures (e.g. committees for regulation of standards), regulation of biofuel markets, creation of incentives, regulation of trade, introduction of sustainability certification schemes and promotion of research and development. In sub-Saharan Africa, South Africa and Mozambique are among the countries which have produced comprehensive policy strategies for guiding biofuel development (Janssen and Rutz, 2012). In South Africa, the policy document for biofuels called "National Biofuels Industrial Strategy" was introduced in 2007, whereas in Mozambique the biofuel policy was introduced in 2009. Other sub-Saharan African countries (including Botswana, Zambia, Tanzania, Mali, and Ghana) have introduced policy statements on biofuel policy or are in the process of drafting detailed legal and regulatory frameworks for biofuel development (Janssen and Rutz, 2012).

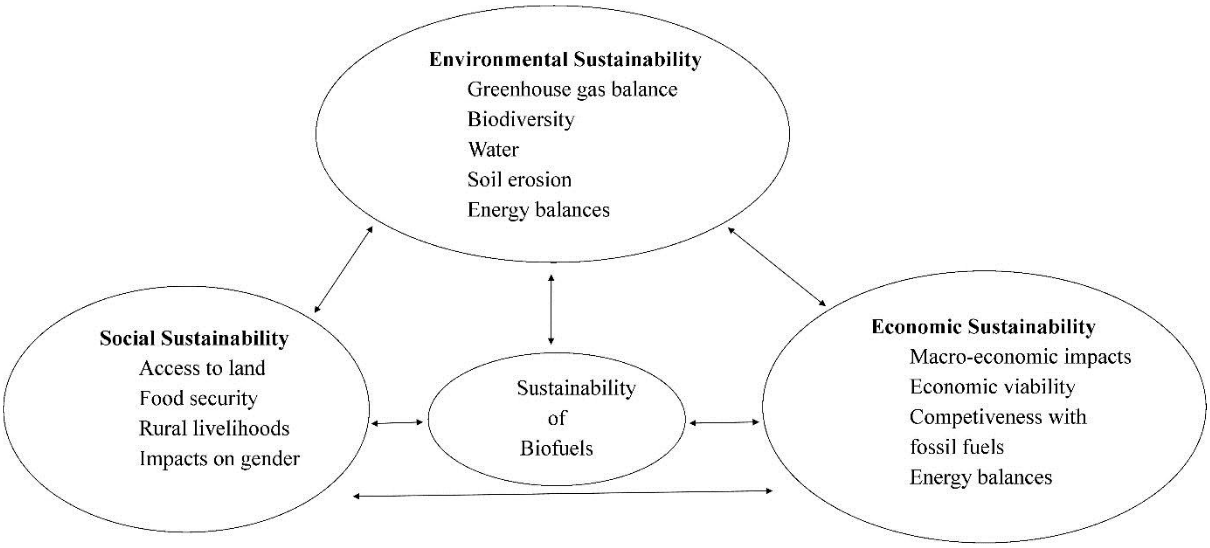
The *Jatropha curcas* L. plant (hereafter referred to as Jatropha) is being promoted by developing countries, international organisations and NGOs as potential feedstock for the production of Jatropha straight vegetable oil (SVO) which could be directly used as a household energy source or transesterised to biodiesel (Openshaw, 2000). Jatropha is native to Mexico and Central America but it is widely grown in the tropics of Central America, Africa and Asia (Contran et al., 2013). In Asia, cultivation of Jatropha is being tried in the large and rapidly growing economies of China and India, where there are mandates for the use of biofuels (Contran et al., 2013). In southern Africa, several countries, including Mozambique, Malawi, Zambia and Tanzania are growing Jatropha. However, the crop has been banned in South Africa based on perceived invasiveness, mainly because it has been listed as a potential noxious weed in Australia (von Maltitz et al., 2014). Gasparatos et al. (2015) contend that this ban of Jatropha was not based on any scientific proof, hence these authors quote studies in Zambia and Burkina Faso which suggest that the fear of invasiveness could have been overhyped. In

Botswana, the Ministry of Minerals, Energy and Water Resources assessed the potential for the production and use of biofuels through a feasibility study undertaken in 2007. The study recommended Jatropha as a suitable feedstock for the production of biodiesel in Botswana (EECG, 2007). Currently, Jatropha is only grown for research purposes in Botswana and there are no commercial plantations (Kgathi et al., 2011; von Maltitz, 2014).

The literature on Jatropha biofuels in sub-Saharan Africa suggests that the global potential of Jatropha biofuel production was greatly exaggerated during the period 2000 – 2008. This is referred to in this paper as the "global Jatropha biofuel hype" (Von Maltitz et al., 2014). Biofuel production was a new phenomenon in most countries of southern Africa during this period; Zimbabwe, South Africa and Malawi were the only countries in the region which had produced biofuels (sugarcane-based bioethanol) before this time period (von Maltitz et al., 2014). In addition to the biofuel development drivers of energy security, climate change, foreign exchange savings and rural development, the Jatropha biofuel "boom and bust" was also driven by the following factors (von Maltitz et al., 2014): 1) the belief that the crop could restore degraded lands, 2) the belief that the crop had high yields even in semi-arid conditions, 3) the belief that Jatropha production had no adverse impacts on food security, and 4) the creation of a biofuel market in the European Union, stimulated by European Union Directives, which encouraged biofuel investment in developing countries (Commission of European Communities, 2012). These factors have been revisited later in this paper. This paper builds on the previous studies on Jatropha biofuels in sub-Saharan Africa (Gasparatos et al., 2015; von Maltitz et al., 2014; Romijn., 2011 and 2014; Achten et al., 2015), assessing the implications of the experiences of Jatropha biofuels on biofuel development and policy in Botswana. The general objective of this study is the assessment of the sustainability of Jatropha biofuels in southern Africa in social, economic and environmental terms. The following research questions are critical in understanding this general research objective: 1) What are the key Jatropha biofuel business models in southern Africa and how are they interlinked? 2) What are the environmental, social and economic impacts of Jatropha biofuels on sustainability and their associated trade-offs? 3) What are the implications of the results of this study for biofuel policy in Botswana? The rest of this paper is organised as follows: Section 2 presents a conceptual framework for analysing the sustainability of biofuel projects in southern Africa. Section 3 describes the study area and methods used in this paper while sections 4, 5, 6 and 7 discuss the results of the literature review. Section 8 and 9 suggest policy recommendations and conclude the paper.

2.0 Sustainability and biofuel development: A conceptual framework

The Brundtland Commission defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WECD, 1987:57-9). In economics, issues of sustainability are clearly articulated in the context of "capital theory approach", and scholars on this subject have two approaches of "weak sustainability" and "strong sustainability" (Stern, 1997). The "weak sustainability" approach is based on the neo-classical assumption that all forms of capital are substitutable, so it is indifferent about the forms in which capital bequests are passed to future generations (Pearce, et al., 1994). Advocates of the "strong sustainability" approach, embraced mainly by some ecological economists and ecologists, contend that different forms of capital are not substitutable for each other and therefore they should not be depleted. For instance, "critical natural capital" which is crucial for human survival, does not have any substitutes, hence it may not be replaced when depleted. This paper adopts a meso-sustainability approach which permits the application of the weak sustainability approach up to a point where certain depletion rates and thresholds of the degradation of vital ecosystem services may not be exceeded (Hardi, 2007). This approach plays a mediating role between different forms of capital and it is conceptually situated between the two extremes of weak and strong sustainability (see Victor, 1991; Stern, 1997).



< Fig.1 A conceptual framework on sustainability of biofuels>

Figure 1 provides a simple conceptual framework utilised in this paper to analyse impacts of the production and use of biofuels on sustainability. Biofuels are considered sustainable if their production and use do not have adverse effects on environmental and social sustainability and at the same time satisfy the criterion of economic sustainability. These three concepts of sustainability are multidimensional and also interlinked (Fig. 1). Economic sustainability of Jatropha biofuel projects is mainly determined by factors such as seed yield of the tree, oil market price, production costs, types of business models used and the global prices of crude oil. In the long run, the economic viability of Jatropha projects may be improved by reducing production costs or by increasing the yield by plant breeding. As Fig 1 indicates, the key considerations of social sustainability of biofuels include access to land, food security, rural livelihoods, impacts on gender and distributive justice (Blaber-Wegg et al., 2015). These considerations are driven by factors such as type of land use, land tenure and transfer procedures, business models used, and biofuel policies adopted.

The key environmental sustainability issues of concern include greenhouse gas balances, impacts on biodiversity, energy balances, pollution and water resources (van Eijck et al., 2014). Impacts of Jatropha production and use on environmental sustainability depend on type of land used, type of the business models used (refer to section 4) and biofuel policies adopted (Gasparatos et al., 2015). For instance, the plantation business model is associated with negative or low greenhouse gas savings because it tends to clear original vegetation when cultivating biofuel crops. If biofuel crops are cultivated on former agricultural lands, they significantly contribute to savings on greenhouse gases.

In summary, the sustainability assessment explores the inter-linkages of the three sustainability criteria, in part by analysing their associated trade-offs. The trade-offs are the extent to which the benefits made in one aspect of sustainability are achieved at the expense of another aspect of sustainability. In general, there is no business model without any trade-offs, but better decisions on the sustainability of biofuels may be made if the trade-offs are known.

3.0 Study areas and methods

The study areas examined for this paper are the main Jatropha growing countries of the Southern African Development Community (SADC): Mozambique, Tanzania, and Zambia. Examples are also drawn from other African and Asian countries for comparison. The SADC countries are at varying levels of economic development with South Africa being the most developed and Malawi being the least developed in terms of per capita income, human development indicators, and level of industrialisation (SADC, 2013). Although southern Africa is endowed with energy resources, the distribution of these resources is uneven and dominated by fossil energy sources (Wakeford, 2006). Overall, the SADC region is a net energy exporter and also a net petroleum exporter, mainly because of the vast coal resources produced by South Africa and high oil production by Angola (SADC, 2006). In 2013, Angola produced 1.87 million bbl/d of liquid fuels, which was 32% of the total oil production in sub-Saharan Africa (US Energy Information Administration, 2013).

Information for this study was obtained mainly from a review of more than 40 peer-reviewed papers on Jatropha biofuels in southern Africa and other parts of the developing world, published in high profile academic journals on aspects of energy and development. In addition, information about the status of Jatropha biofuel policies in Botswana was extracted from completed questionnaires used in the second phase of the research project on stakeholder views of biofuel policies in Botswana (Kgathi et al., 2016). Thirty policy-makers, researchers and NGOs based in Gaborone, the capital of Botswana, were interviewed. Researchers selected were those working on biofuels in Botswana, including those who participated in the Government-sponsored Jatropha Research Project.

The stakeholder survey questionnaire included open-ended and flexible questions on issues such as drivers of biofuel development in Botswana, type of biofuel business models, and perceptions about the potential impacts of Jatropha biofuels in Botswana. The results of the stakeholder-research are reported in a separate paper (Kgathi et al., 2016) with selected highlights from the findings reported in this paper to assist in the interpretation of the literature results in the section 10 on “Discussion and policy implications”.

4.0 Models of Jatropha projects and value chains

As several case studies illustrate, many countries expanded their jatropha plantations in sub-Saharan Africa during the period of the global Jatropha biofuel hype (2000 to 2008). Jatropha projects differ, depending on the country and its development goals (van Eijck et al., 2012). Gasparatos et al. (2015) classified these projects in four main types: 1) small scale rural electrification (Type 1), 2) large scale farms or mines which produce biofuels for their own consumption (Type 2), contract farming (also known as farmer-centred model or out-grower model) (Type 3) whereby farmers are contracted by private companies to grow crops on their own land (van Eijck et al., 2012) and large scale commercial plantations (Type 4) for producing biofuel feedstocks for both export to other countries and local consumption..

In southern Africa, Type 1 projects are mainly in the form of small-scale rural electrification projects promoted mainly by NGOs and development agencies to produce biodiesel for local rural electrification and they are found in countries such as Mozambique and Tanzania. In these countries, Jatropha is grown on small-scale plantations or in the form of hedges. Oil is produced from Jatropha for various purposes, including the powering of multi-functional platforms which provide rural communities with energy for rural electrification and other services such as water pumping and charging batteries (Gasparatos et al., 2011). Type 2 projects are common in Zambia where they are used in large-scale commercial farms for producing Jatropha feedstock for use on farms or mines.

In Type 3 projects, farmers are contracted by private companies to grow crops on their land (van Eijck et al., 2012). These projects are found in several southern African countries such as Zambia, Malawi, Mozambique and Tanzania. For example, the companies Marli Investment and Bioenergy Resources in Zambia and Malawi have been involved in Jatropha outgrower contract farming since 2003 and 2006, respectively. Type 4 projects are large commercial plantations in southern Africa which had planned to produce Jatropha seeds for export as well as local consumption but ended up producing for local consumption in most countries. Examples of these include big companies such as D1 Oils and Sun Biofuels which were operating in southern Africa and some of their projects have now collapsed as will be described later in this report (Von Maltitz et al., 2014). While Type 1 and Type 3 business models are described by scholars as inclusive business models since they involve local communities in the development process, Type 2 and Type 4 models are exclusive; their contribution to rural development and poverty alleviation is either marginal or almost absent (Gasparatos et al., 2015; van Eijck, 2014).

The main stages in the value chain of Jatropha biodiesel production include cultivation, seed processing and marketing, Jatropha SVO production and biodiesel production (Contran et al., 2013; van Dorp, 2013). Because most Jatropha projects in southern Africa collapsed before they reached the stages of oil and biodiesel production, the emphasis of this paper is on the stage of cultivation. To produce oil, the husk of the Jatropha seed, which is estimated to contain 30-35% of oil, is removed, then dehulled to separate the kernel from the shell. Oil is extracted from the kernel which produces the seedcake, and finally crude oil is cleaned to produce pure oil (Contran et al., 2013). Different methods are used to transform Jatropha SVO into biodiesel such as blending and transesterification, the former involving the mixing of Jatropha SVO with fossil diesel to produce Jatropha SVO-diesel blends of the recommended proportions and the latter involving the transformation of SVO into methyl esters (biodiesel) using methanol (Contran et al., 2013; Van Dorp, 2013). In large processing plants, the resulting mixture of the process of transesterification is allowed to settle resulting in a bottom layer consisting of glycerin, excess alcohol, catalyst and other impurities, and an upper layer consisting of biodiesel, alcohol and some soap (Raja et al., 2011). Warm water is added to the biodiesel to separate the biodiesel from the soap and other remnants of the catalyst (Yusoff, et al., 2013). Jatropha SVO can be used directly for transport fuel in some engines, but in general its use is not satisfactory in traditional engines, mainly because of high viscosity (Contran et al., 2013).

5.0 Economic sustainability of Jatropha projects

5.1 Macro-economic impacts

Macro-economic studies based on general equilibrium models, which used Jatropha yield data based on assumptions rather than actual field data, have found that investments in biofuels will enhance economic growth and alleviate poverty in southern Africa. General equilibrium modelling studies in Mozambique and Mali, where Jatropha was the main feedstock for biofuels, concluded that biofuel projects could contribute significantly to GDP and employment generation. For instance, Arndt et al. (2010) found that biofuel investments in Mozambique based on bioethanol produced from sugarcane in large-scale plantations and biodiesel produced from Jatropha out-grower contract farming were expected to increase economic growth by 0.65% and to reduce poverty by 5.9% by 2015. They also estimated that the cultivation and processing of Jatropha into biodiesel would create 455 000 jobs. Jatropha out-grower configuration was considered more pro-poor than the plantation model due to its use of unskilled labour, benefits accruing to smallholders in the form of land rents, and provision of inputs and extension services for biofuel feedstocks associated with food production technology spin-offs (Arndt et al., 2010; Ewing and Msangi, 2009). However, a study undertaken in Mozambique by Thurlow (2008, cited by Arndt et al., 2010) indicates that the economic growth generated by Jatropha projects has a poverty-growth elasticity of -0.43

which is lower than that for other crops such as maize, sorghum and horticulture with elasticities of -0.73, -0.65 and -0.48, respectively. This suggests that distributional and poverty reduction impacts associated with economic growth from Jatropha investment is lower than that from the conventional crops.

The Mali general equilibrium study revealed that investment in Jatropha biodiesel would increase GDP if idle lands were used for Jatropha cultivation, while if existing arable lands were used, there would be a slight decrease in GDP. There would be a reduction in poverty when either idle lands or existing agricultural lands were used, but the former would have a greater impact on poverty reduction than the latter (Boccanfuso et al., 2013). Gasparatos et al., (2015) cautions that most of these macro-economic studies could have exaggerated the impacts of Jatropha biofuel projects since they used Jatropha yields based on assumptions rather than the actual field data. For instance, there was a claim during the period of the Jatropha biofuel hype that the yields of Jatropha projects could reach a figure of 12 t ha^{-1} yr^{-1} (Openshaw, 2000). This claim has subsequently been proved to be incorrect.

5.2 Economic viability of Jatropha projects

5.2.1 Projects that collapsed

Most Jatropha projects collapsed or disinvested in southern Africa and other parts of sub-Saharan Africa towards the end of the period 2000-2008. Most of these projects included Type 4 Jatropha ventures aimed at producing biodiesel for national consumption or export to Europe, including those such as Sun Biofuels in Mozambique and Tanzania, ESV in Mozambique, and D1 Oils in Mozambique and Zambia (von Maltitz et al. 2014; Gasparatos et al. 2015). For instance, Romijn et al. (2014) found that all large plantations had collapsed in Tanzania during the period 2008-2012, except the plantation of the former Sun Biofuels in Kisarawe which had been sold to a Mauritius-based holding called Thirty Degrees East. In Mozambique, there were five large plantations covered by the survey, established between 2007 and 2010.

A scoping study undertaken in early 2013 in the Jatropha producing countries Ethiopia, Indonesia, Mozambique, Tanzania and Zambia, indicates that most of the companies which were involved in Jatropha production either collapsed, disinvested, or took a long time to move into production. In Mozambique, the total land authorised for biodiesel production was 111 797 ha but only 4 030 ha or 3.6% of this was cultivated by 2013 (Table 1). In Zambia, the number and scale of biodiesel projects were reduced. There were no large-scale commercial projects in this country as most of them were either scaled down or abandoned (Locke and Henley, 2013). In addition, several projects in these countries took a long time to move into production for reasons including difficulties in acquiring capital for processing of the feedstock as was the case in Zambia; difficulties in achieving economic viability of the Jatropha feedstock (e.g. in Mozambique) because there was no policy to support biofuels as fossil fuels were still being subsidised in some of the countries (e.g. in Zambia); and because of bureaucratic delays in obtaining land use licences (e.g. in Mozambique) (Locke and Henley, 2013).

< Table 1. Overall land-use for biodiesel production in Mozambique, Zambia and Tanzania (2013) >

	Mozambique	Zambia	Tanzania
Planned area for cultivation (ha)	127 732	927 649	202 364
Total area authorised (ha)	111 797	600 173	42 211
Actual area under cultivation (ha)	4 030	3 925	1 370
Total area under cultivation as % of area authorised (ha)	3.60%	0.65%	3.25%

The main reason for the failure of Jatropha projects was lack of economic viability mainly due to low yields. A study of 23 projects in Mali, Mozambique, and Tanzania revealed that most Jatropha projects either had limited economic viability or were not viable. Jatropha plantation projects were either not economically viable or only marginally so, whereas most smallholder projects were unviable, except those that used hedgerows in economically poor areas (Romijn et al 2014). Gasparatos et al. (2015) also noted that most of the smallholder Jatropha projects tended to have a high internal rate of return (IRR) only when unsalaried family labour was used. A study undertaken in northern Tanzania revealed that the net present value (NPV) for a five-year investment in a Jatropha project on lands with yields of 2 t ha^{-1} yr^{-1} was negative, with loss estimated at US$ 261 ha^{-1}y^{-1}. However under an assumption of a yield of 3 t ha^{-1} yr^{-1} and when Jatropha was intercropped with sunflower, the investment of the project was slightly profitable with a NPV of US$ 9.00 ha^{-1}y^{-1} (Wahl et al., 2009). According to von Maltitz et al., (2014), lack of economic viability of Jatropha projects was attributed to the following factors: 1) lower than anticipated yields of Jatropha, 2) underestimation of the production and distribution costs of Jatropha, 3) changes in the price of crude oil, 4) delays in the production of Jatropha seeds, and 5) changes in the way investors perceived Jatropha projects. Elaboration of some of the key factors follows.

Low yields of Jatropha

The literature on Jatropha biofuel indicates that the yields of Jatropha seeds were a key factor contributing to the lack of viability of Jatropha biofuels in most countries of southern Africa. During the time of the global Jatropha biofuel hype, most of the projects had expected to obtain an average yield of up to 12 t ha^{-1} yr^{-1} for the Jatropha seeds (Openshaw, 2000). According to Edrisi et al., (2015), a yield of 4-5 t ha^{-1} yr^{-1} is required in order for a Jatropha project to be economically viable. These authors further analysed that the actual yields of Jatropha projects were lower than expected, estimated to be 0.35 t ha^{-1} yr^{-1} in South Africa, 2 t ha^{-1} yr^{-1} in Tanzania and 0.5 t ha^{-1} yr^{-1} in India. Thus, even though Jatropha grows well in arid and semi-arid conditions, the actual seed yields are generally lower than expected. To obtain an economically viable yield of Jatropha seeds, rainfall of 1,500 mm yr-^{1} is required (Trabuco et al., 2010). Studies undertaken in Honduras, Mali and Mozambique show that oil yields of Jatropha can vary from as low as 250 L $ha^{-1}yr^{-1}$ in areas with insufficient rainfall and soil nutrients to as high as 1,250 L $ha^{-1}yr^{-1}$ in areas with sufficient water and soil nutrients (Romijn, 2011). Even in areas of fertile soils, the yield of Jatropha is not cost competitive with that of other crops such as sunflower (Achten et al., 2008). In addition to water availability and climatic conditions, Jatropha yields are also affected by crop management techniques such as spacing between crops and application of inputs (van Eijck et al., 2012).

Costs of producing Jatropha seeds

The costs of Jatropha production, including those of labour for planting, weeding, pruning, harvesting the seeds and transport also contribute to economic viability of Jatropha projects

(Bornman et al., 2013). A case study of Jatropha SVO production in Tanzania revealed that though an increase in inputs contributes significantly to higher yields, this tends to increase production costs, adversely impacting the profitability (Segerstedt and Bobert, 2013). Therefore, increasing inputs may increase production but also reduce the profitability of the Jatropha projects.

van Eijck et al. (2014) also pointed out that the production of the Jatropha feedstock is labour intensive since most of the activities have been done manually. For instance, in Mozambique, it is estimated that one person can harvest only 8-24 kg of seeds per day if dehulling is included, or up to 40 kg if the more labour intensive activity of dehulling is excluded. Therefore, the costs of labour tend to account for a very large proportion of the production costs of the Jatropha feedstock and have a high influence on the viability of these projects. However, the amount of labour needed depends on the type of inputs needed and the production per year. In Mozambique and Zambia, the cost of transport tended to be unexpectedly high, mainly because small quantities of seeds were collected from scattered areas in rural areas. In addition, the high global price of oil resulted in an increase in the price of fuel used in transporting the harvest, hence negatively affecting the profitability of Jatropha projects (von Maltitz et al., 2014).

Global change in the price of crude oil

A number of authors have calculated breakeven points or parity price lines at which biofuels will be competitive with fossil fuels using combinations of crude oil and feedstock prices (Teyner and Taheripour, 2007); Miranowski and Rosburg, 2013). Most of the calculations excluded taxes and subsidies and also assumed the status of technology to be constant (Tyner and Taheripour, 2007). At price combinations above a parity price line, a biofuel would be profitable because of higher crude oil prices and lower feedstock prices, whereas at price combinations below a parity line, a biofuel would not be profitable because of lower crude oil prices and higher feedstock prices (FAO, 2008). In 2008, most Jatropha processors in southern Africa had expected to make reasonable profits on their investments because the price of crude oil had reached a high of US$ 145/barrel. When the price then sharply dropped to US$ 30.00/ barrel at the end of 2008, many Jatropha biofuel investments became unprofitable (Romijn et al., 2014). The situation had changed by 2012 since the managers of the three oldest Jatropha plantations in Mozambique were expecting to sell their Jatropha SVO at Mozambican Metical (MT) 18.25-35.80 L^{-1} which was below the local petroleum diesel price of MT 35 to 38 L^{-1} (Romijn et al., 2014). In January 2016, the situation had changed again as the price of crude oil had dropped to a figure below US$ 40.00, hence Jatropha SVO was expected to be uncompetitive again.

Delays in production

The scoping report on biofuels in developing countries indicates that Jatropha projects took a much longer time than anticipated to move into production for several reasons (Locke and Henley, 2013). For instance, in Mozambique, it is reported that investors pulled out because of delays in project implementation, delays in acquiring land use licence, and evidence of the lack of economic viability of these projects. In Zambia, the Government had continued to subsidise fossil fuels and at the same time supported Jatropha projects; there was lack of capital to process biofuels and lack of information about the gestation period of Jatropha projects. According to Kalinda et al. (2015), subsidisation of fossil transport fuels coupled with delay in setting up a standard price for biodiesel, absence of appropriate energy policies, and lack of monitoring and evaluation of Jatropha projects also contributed to delays in production and lack of viability of Jatropha biofuel projects.

5.3 Resilient Jatropha Projects

The previous section has shown that although there are many contributory factors behind the collapse of biofuel projects, the key contributory factors are the low seed yield of Jatropha, high production costs, and decline in the global price of crude oil. Several case studies illustrate that Jatropha seed production of both smallholder and large scale projects is not viable or it is only marginally so (Wahl et al., 2009; van Eijck et al., 2013). As already stated, most of the Jatropha biofuel projects that collapsed in southern Africa were those involving large plantations. Concerned about this problem, Romijn et al. (2014) suggested that large-scale projects should not be implemented in the future until better varieties with higher yields are found.

In 2013, Von Maltitz et al. (2014) analysed the characteristics and management practices of two Jatropha companies that had not collapsed and also showed signs of economic viability in the long-term. These were Bioenergy Resources Limited (BERL) in Malawi, a small-holder contract farming company, and Niqel in Mozambique, a large-scale biofuel company. These companies had in the initial stage based their economic planning on realistic and modest yields of 1.9 t ha^{-1} in the case of BERL and 3 t ha^{-1} in the case of Niqel, estimates that were much lower than those of most companies. Projected economic returns from the Jatropha investment was therefore based on these modest yields. von Maltitz et al. (2014) further suggests that these companies did not expect very high economic returns from Jatropha investment and their projected overheads were therefore based on modest returns from their investment. The company Niqel was described as having the lowest establishment costs per unit area planted in southern Africa and also more successful than other large-scale Jatropha biofuel projects. BERL had limited production costs as well because it is an out-grower contract farming company with cultivation costs mainly borne by the small-holder farmers (von Maltitz et al., 2014). Romijn et al., (2014) also recommended that expensive capital intensive operations of Jatropha biofuel projects should be avoided in order to reduce production costs.

5.4 Economics of Jatropha biodiesel projects

Several studies indicate that the competitiveness of Jatropha biodiesel and SVO with petroleum diesel prices is mainly determined by the yield of the crop, cost of the feedstock, and price of petroleum diesel (Mulugetta, 2009; van Eijck et al., 2012). A sensitivity analysis by Mulugetta (2009) suggests that the cost of the Jatropha feedstock was a major factor which determined the viability of Jatropha biofuel projects in Tanzania. Using 5%, 9% and 12% discount rates over a period of 15 years, Mulugetta (2009) estimated the levelized potential revenue of Jatropha biodiesel in this country to range from US$ 0.06 to US$ 0.10 L^{-1}, basing these calculations on data from Europe and Central America. The break-even cost of Jatropha biodiesel was estimated at US $0.70 L^{-1}, *ceteris paribus*, hence there was a net gain when the price of diesel was above this cost price and a net loss when the price was lower. However, van Eijck et al (2012) revealed that in Tanzania the cost of Jatropha SVO ranged from US$ 0.61 to 1.07 US$, whereas the cost of biodiesel ranged from US $ 0.89 to US $1.35 L^{-1}. The cost of Jatropha SVO was competitive with that of petroleum diesel in cases where family labour was used, whereas biodiesel was more expensive than fossil diesel (van Eijck et al., 2012).

There is a lack of information on the economic performance of Jatropha biofuel projects in southern Africa beyond the plantation stage of biofuel projects since most of the projects have collapsed. A few projects that have not collapsed and are reaching the stage of maturity include BERL smallholder project in Malawi which grows Jatropha as hedgerows along perimeter fences (von Maltitz et al., 2016). BERL aims at achieving a 9% blending of petroleum diesel with Jatropha oil to contribute to energy security in Malawi. To achieve this target, it will be necessary for the project to reach a seed yield of 0.92 kg yr^{-1} to 1.3 kg yr^{-1} yet the actual yield in 2013 was only 0.19 kg $tree^{-1}$ of dehusked seeds (von Maltitz et al., 2016).

6.0 Social Sustainability

6.1 Access to land

In recent years, particularly during the period of the global Jatropha biofuel hype, there has been increasing discussion of land acquisitions for the production of biofuel crops in sub-Saharan Africa by external investors (Graham et al., 2011; Vermeulen and Cotula, 2010, Gasparatos et al., 2015). Critical issues associated with land acquisition include: 1) information about previous land-use since this provides an indication of the opportunity cost of land transfer , 2) the magnitude of compensation paid for the loss of land rights, 3) the degree of transparency in the transfer of land rights, and 4) the extent to which accepted procedures of land transfer were followed (Gasparatos et al., 2015).

The production of biofuel crops such as Jatropha in sub-Saharan Africa takes place mainly on communal land. The legal guidelines for the transfer of land rights differ from country to country. In most countries of southern Africa, it is necessary to obtain a land lease. In Tanzania, "village land" is converted to "general land", which is owned by the central government, to give biofuel investors a land lease (van Eijck et al., 2014). In Botswana, there are no land leases issued to biofuel investors as yet, but it will be necessary to convert land registered under customary tenure to common law to lease the land to foreign investors (Kgathi et al., 2011). In general, the production of biofuel feedstocks in sub-Saharan Africa has caused loss of access to land among rural households, with adverse effects on their livelihoods, particularly when biofuel projects subsequently collapsed. Such impacts on access to land were more characteristic of large-scale biofuel projects than on small-scale out-grower projects, as land rights are not transferred in the latter. The paper's discussion on land transfer will therefore focus on large scale plantations.

In Mozambique, where communal land is owned by the state, the transfer of land to biofuel investors during the period of the global Jatropha biofuel hype has followed the appropriate legal procedures of obtaining a DUAT, which is the right to use and develop the land, in that local communities and authorities were consulted (Romijn et al., 2014). There were, however, minor conflicts associated with the failure of biofuel investors to deliver some of their promises. For instance, Energem, a renewable energy company which was located in Gaza District in southern Mozambique, had promised to build schools and hospitals and to provide water boreholes for local communities in exchange for the land. As of April, 2009, the company had not fulfilled its promises, and it was experiencing financial problems (Ribeiro and Matavel, 2009). The local communities were concerned about the failure of the company to fulfil its promise.

A survey undertaken by Romijn et al. (2014) in Tanzania, revealed that Jatropha projects were mainly in the form of out-grower schemes at the time as most of the large scale-plantation projects had collapsed. The authors noted that there were long-term land access problems in Tanzania because it was not clear whether the land rights transferred to investors would be returned to local communities after the large-scale biofuel plantation projects had collapsed. As van Eijck et al. (2014) put it, the land was former "village land" which was transferred to the central government in order to give leases to biofuel investors and it was already transferred back to the central government. When the company Sun Biofuels collapsed, workers obtained only access to the sites of their graves and water points (Romijn et al., 2014). Also, when the company BioShape collapsed in Tanzania it was not clear whether the land would be returned to the local communities (van Eijck et al., 2014).

6.2 Rural livelihoods

The main livelihood opportunity for local communities in large-scale Jatropha projects was in the form of employment, though some projects also made a contribution to education, health, water supply and infrastructural development. A study undertaken in rural Tanzania showed that Jatropha contributed 30% to the total income of all livelihood activities of small-scale subsistence farming households who were involved in its cultivation. However, it contributed only 1% to 2% to the total income of households who were mainly involved in "cash crops and/ or skilled off-farm employment" (Achten et al., 2015).

Field surveys undertaken in Mozambique, Tanzania and Mali by Romijn et al (2014) revealed that Jatropha projects had created 600 permanent jobs and 1000 temporary jobs. Most of the permanent jobs were created in Mozambique, where the large plantation business model was dominant, whereas most of the temporary jobs were created in Tanzania, where the smallholder-based model was more common. In general, salaries of the Jatropha project workers were very low in southern Africa although they were above the minimum wages being paid in the agricultural sector. According to Ribeiro and Matavel (2009), the Jatropha company Energem paid its Mozambican workers a minimum wage of 1 650 MT per month (US$ 60) which was above the minimum wage rate, whereas Totoma in Mali paid its plantation workers CFA 500-750/day (US$ 1-1.50/day). In general, contract farming offers economic benefits to the wider economy as compared to the plantation business model which benefits only a few people (Gasparatos et al., 2015).

6.3 Food security

Biofuel development in southern Africa has resulted in both negative and positive impacts on food security (van Eijck et al., 2014; Ribeiro and Matavel, 2009; Romijn et al., 2014). The concept of food security is discussed broadly in the context of the four dimensions: 1) food availability, 2) food access, 3) food stability and 4) food utilization (FAO, 2008). Biofuel projects may adversely affect food availability if the land and other inputs for food production (water, labour and other resources used for food production) are instead used for the production of biofuels. These projects may cause lack of access to food if they lead to an increase in food commodity prices, reduction in household income or if they worsen the physical access to food markets (Locke and Henley, 2013). The pressure on food stability or chronic food insecurity is likely to be increased in the face of economic and environmental shocks such as unemployment, changes in food prices, bankruptcy of biofuel projects and switching of land use from food crops to biofuel projects (Locke and Henley, 2013). Finally, utilization of food resources is concerned with the wider issues such as access to energy services, clean water, sanitation and medical services (Faaij, 2008). These aspects are important because they determine food consumption patterns of households which are in turn a key determinant of their nutritional status (Faaij, 2008; Locke and Henley, 2013).

Overall, research undertaken in southern Africa indicates that the plantation business model is more associated with adverse effects on food security, particularly when biofuel projects collapse in the absence of an exit strategy (Locke and Henley, 2013; Romijn et al., 2014; Gasparatos et al., 2015). In southern Africa, agro-biofuel Jatropha projects have in most cases resulted in negative impacts on food availability, although in a few instances, the impacts were positive. A survey of workers in five Jatropha plantations in Mozambique revealed that the labour-time for their own food production had significantly declined from 20-25 h/week to 4-14 h/week as a result of their involvement in biofuel plantations (Romijn et al., 2014). However, the farm workers perceived the Jatropha project to have improved their food security on average (Romijn et al., 2014), probably because their loss in food security associated with the reduction in their labour time was compensated by cash income from their wages which enabled them to purchase food. Establishment of a Jatropha biofuel plantation by Energem Resources Inc in the Bilene-Macia District of Gaza Province, Mozambique, in 2007 is said to have resulted in a negative impact on food availability because it displaced smallholders from their farming areas. In addition to diversion of land from food production, it also diverted labour and other forms of production. The company became insolvent in 2011, resulting in loss of employment opportunities. Bankruptcy of a biofuel project contributes to the pressure on food stability, particularly if there is no exit strategy in place as was the case with Energem and other biofuel projects in Mozambique and Tanzania (Schut and Florin, 2015).

A study undertaken in Solwezi, Zambia, among small-scale farmers between 2011 and 2014 revealed that biofuel production resulted in an adverse effect on food availability (Kalinda et al., 2015). The farmers had entered into contractual agreements with companies such as Marli Investment and others on an outgrower basis to produce Jatropha seeds in their fields (Kalinda et al., 2015). Interviews of farmers revealed that the cultivation of Jatropha had resulted in a reduction in the yields of conventional crops of maize and beans; 39% of the farmers said Jatropha had displaced other food crops. There was also an indirect land-use change in that new land was found to establish the displaced food crops. This reduction in the yields of conventional crops was experienced by farmers who integrated Jatropha with other crops (mixed farming) as well as those who practiced mono-cropping.

If Jatropha is planted in hedgerows around fields and homesteads rather than as mono-crop, there can be positive impacts on food security. This has been demonstrated by several projects in the southern African region as well as in Mali (Romijn et al., 2014; van Eijck et al., 2015). Examples in southern Africa include the business models of companies such as Bioenergy Resources Limited (BERL) in Malawi and *Ajuda de Desenvolvimento de Povo para Povo* (ADPP) in Mozambique. These companies buy Jatropha seeds from farmers who plant them as hedges around crops and homesteads. A recent study by von Maltitz et al (2016) revealed that the BERL smallholder project in Malawi had modest financial returns which were highly appreciated by the local communities, particularly those who experienced high prevalence of poverty. The study further indicated that the project was associated with little direct land-use change since Jatropha was grown as hedgerows along the perimeter of the farms. This project resulted only in a small impact on land for other crops.

7.0 Environmental Sustainability

7.1 Biodiversity

Biodiversity plays a major role in underpinning ecosystem processes, or it could be described as a foundation for ecosystem services. It can also be an ecosystem service in its own right (Mace et al., 2012). The following factors are considered key drivers of loss of biodiversity associated with biofuels: 1) habitat destruction or land-use change, 2) invasiveness of species, 3) pollution, and 4) climate change. Of these, habitat destruction is known to be a major factor contributing to loss of biodiversity, followed by invasiveness of species (Gasparatos et al., 2015).

According to Gasparatos et al., (2015), cultivation of biofuel crops in sub-Saharan Africa takes place on four main types of land: 1) former agricultural lands, 2) abandoned agricultural lands, 3) degraded land and 4) naturally vegetated land. It has been found that the cultivation of Jatropha in Zambia resulted in both direct land-use change and indirect land-use change (German et al., 2011). Only 22% of small-holders said their cultivation of Jatropha resulted in opening-up of new fields, while 20% said it resulted in both direct land-use change and indirect land-use change (German et al., 2011). The latter occurred because farmers relocated to other areas to find new land for growing food crops to replace the land under Jatropha. It was estimated that 44% of the land under Jatropha was converted from natural forests. However, large-scale plantations tend to have a greater impact on biodiversity since the natural vegetation is removed. According to van Eijck et al (2013), the company BioShape had planted 400 ha of 34 000 ha acquired with Jatropha and was planning to reach a target of 80 000 ha in 2018. Some of the forests and woodlands planned for plantations were very rich in biodiversity, with average Shannon indices of 2.52 and 2.18, respectively. Therefore, the large plantation model is more associated with risks to biodiversity than the smallholder model.

Jatropha has been categorised as an invasive species in several countries such as Australia, USA and Hawaii, South Africa and the Galapagos Islands (Negussie et al., 2013). As a result, the cultivation of this crop has been banned in some of these countries, not based on any solid scientific evidence. Several Asian and African countries have promoted Jatropha without any apparent cognisance of potential invasiveness. Recent observations made, and ecological field experiments undertaken in Zambia and Burkina Faso revealed that there is no evidence that Jatropha is an invasive crop (Negussie et al., 2013). These studies did not observe any “spontaneous regeneration” in land-use systems adjacent to those of Jatropha plantations, the dispersal of Jatropha seeds was limited and Jatropha seeds and fruits were eaten by rodents and shrews (Negussie et al., 2013; Negussie et al., 2015).

Finally, Jatropha feedstock production uses less agro-chemicals than sugarcane feedstock, suggesting that pollution-related adverse impacts on biodiversity are lower (Batidzirai and Johnson 2012; Gasparatos et al., 2015). However, the literature in southern Africa has shown that the yields of Jatropha are generally low, suggesting that larger areas may need to be cultivated to increase the output of Jatropha seeds, leading to biodiversity loss. Jatropha production can be used as a strategy for mitigation of soil pollution in southern Africa since it has been proven that it is effective in phytoremediation of polluted soils (Agamuthu et al., 2010). Overall, environmental impacts of Jatropha cultivation on biodiversity depend on production practices and how land-use change is managed (FAO, 2008).

7.2 Water resources

One of the perceived benefits of Jatropha was that it has very low water requirement of 200 mm to 300 mm per year. However, it is now known that the water requirements of Jatropha are much higher than expected. As Rao et al. (2012) puts it, Jatropha can use large amounts of water in order to obtain high yields and “luxurious growth”. Research undertaken by Ribeiro and Matavel (2009) in Mozambique showed that it is necessary to irrigate the Jatropha crop, particularly at its early stage of development, even in rainfall regimes of 800 mm to 1 400 mm per year. In situations where Jatropha was not irrigated, its rate of germination tended to be low and it was vulnerable to diseases, stresses and shocks (Ribeiro and Matavel, 2009). Results of a study undertaken by Maes et al. (2009) on climatic growing conditions, using Jatropha herbarium specimens collected in Mexico, demonstrated that Jatropha naturally grows in areas with an average annual rainfall of more than 944 mm/year. Most of the specimens (95%) were from areas with this mean annual rainfall. The results reveal that Jatropha is not grown much in semi-arid conditions, and not grown at all in arid conditions.

7.3 Energy balance

Energy Return on Investment (EROI), which measures the proportion of energy produced from biofuels compared to the inputs of fossil energy sources used, is one of the indicators of the energy gain from biofuels and it is a key indicator of the impact of a biofuel on energy security (Gasparatos et al., 2015). Life cycle analysis (LCA) of the production chain of Jatropha biofuels indicates net energy gains. Review of literature on energy balance of Jatropha biodiesel shows positive values of the EROI of more than 1 in some countries of sub-Saharan Africa. Studies carried out in West Africa estimated the EROI values to be in the range of 1.8 to 4.7. In addition, Eshton et al. (2013) estimated the EROI, for Jatropha biodiesel in Tanzania to be 2.3, indicating a significant energy return on investment. Most LCA energy balance studies for Jatropha biodiesel in sub-Saharan Africa reveal that the transesterification process accounted for the highest consumption of energy. For instance, Ndong et al. (2009) state that this process used 61% of the total energy consumption, followed by the transport of inputs (15%), and cultivation (12%). The rest of the activities such as refining, cold pressing and distribution accounted for only 12% of the total energy consumption.

7.4 Climate change

The impact of biofuels on climate change depends on the type of feedstocks used and the impacts on land-use change (Table 2). Two seminal studies published in *Scienc*e revealed that most life cycle studies on biofuels before 2008 had not taken into account greenhouse gas (GHG) emissions resulting from land-use change occurring prior to the cultivation of the biofuel crop (Fargione et al., 2008; Seachinger et al., 2008). These studies revealed that GHG emissions from land-use change far exceed the savings from the substitution of fossil fuels by biofuels, and a period of more than 300 years was needed to pay the carbon debt from the palm oil plantations in Indonesia and Malaysia (Table 2). It should be noted that the above-mentioned studies were based on case studies of palm oil and sugar plantations and not Jatropha (Fargione et al., 2008; Seachinger et al., 2008).

A worldwide study by Achten et al. (2013) on Jatropha plantations in arid and semi-arid lands supported the findings of the studies published in *Science*. Carbon debts were calculated for land conversion in low, medium and high average biomass carbon stocks. It was revealed that GHG emissions resulting from the felling of forests before the cultivation of Jatropha was a heavy initial investment which would take a long time to be paid back by the use of Jatropha biofuel (Table 2). Romijn (2011) also revealed that the introduction of Jatropha plantations in virgin Miombo tropical woodlands would result in GHG emissions which exceed the savings resulting from the Jatropha biofuel due to land-use change prior to the cultivation of the biofuel crop (Table 2). The study also found that conversion of wastelands and degraded lands into Jatropha plantations would result in savings in GHG emissions because land-use is changed from low to higher carbon storage with Jatropha trees.

< Table 2: Results of studies on the impact of biofuel development on climate change >

Sources	Type of feedstocks	Countries / regions	Results
Fargione et al. (2008); Searchinger et al., (2008)	Soya beans, sugarcane, palm kernel	Brazil, USA, Malaysia and Indonesia	The land-use change resulting conversion of land into biofuels created a biofuel carbon debt. Palm oil plantations in Indonesia and Malaysia needed to run for more than 300 years to repay the carbon debt. GHG savings from corn ethanol in USA would pay back the carbon debt after 167 years.
Romijn (2011)	Jatropha	Miombo woodlands in sub-saharan Africa	The planting of Jatropha in virgin miombo woodlands can lead to a net increase in GHG emissions due to land-use change resulting in a carbon debt of over 30 years. There is a net reduction in GHG emissions when the plant is grown in wastelands or degraded lands.
Achten et al. (2013)	Jatropha	Global, arid and semi-arid environments	The conversion of semi-arid shrubland to Jatropha is estimated to cause a carbon debt of 24-28 t C ha^{-1} on average, which could be repaid over of a period of 30 years. The minimum Jatropha yield required to repay the debt is 3.5 to 3.9 t of dry seed ha^{-1} y^{-1}.
Achten et al. (2015).	Jatropha	Tanzania	This study estimated the potential of producing Jatropha by small-scale farmers on GHG balance in 20 regions of Tanzania. Jatropha production was estimated to lead to a carbon debt of 1,307,000,000 t CO_2 which would be repaid in 61 yrs.

Several studies have recently been undertaken to determine the life cycle assessment (LCA) impacts of Jatropha biofuels in sub-Saharan Africa. In West Africa, the LCA study by Ndong et al. (2009) revealed that Jatropha biofuels could yield GHG savings of 72%, assuming that the feedstocks were grown on abandoned cotton fields. Another study by Achten et al. (2015) estimated the GHG balance of converting marginal land to Jatropha by small-scale farmers in 20 regions of Tanzania. The GHG emissions resulting from land-use change were not estimated since they are not considered by the LCA model used. Indirect land-use change was not included in the calculations of the GHG balance since marginal lands have limited use in Tanzania. The total area for Jatropha production in the area was 23,763,600 ha, estimated to produce 33,870,000 t of Jatropha seeds, and resulting in reduction of GHG emissions of 15,282,700 t CO_2 equivalent resulting from the sale of seeds and 12,889 t CO_2 equivalent resulting from the sale of oil. Conversion of these marginal lands to Jatropha in Tanzania was estimated to cause a carbon debt of 1,307,000,000 t CO_2 which would be repaid in 61 years. The debt was high because some of the regions, such as Arusha, Dodoma, Kilimanjaro, and Mara had negative GHG balances. The study recommended that Jatropha investments should be limited to areas with low carbon debts (Table 2).

8.0 Discussion and Policy implications

The results of this study, summarised in Table 3, have shown that most of the Jatropha projects in southern Africa have resulted in differential impacts on social, economic and environmental sustainability. Macro-economic studies undertaken in Mozambique and Mali have shown that Jatropha projects have the potential to increase economic growth and alleviate poverty. However, case studies of biofuel projects in Mozambique, Zambia and Tanzania show that most of the Jatropha projects collapsed during their plantation stage before their yields were stabilized during the period 2008-2012 (Gasparatos et al., 2015), mainly due to low yields and high production costs which contributed to their lack of economic viability. The vulnerability of Jatropha projects is also determined by type of business model and management practices adopted. Smallholder projects tend to be more resilient than large scale projects, partly because of lower production costs. von Maltitz et al (2014) revealed that good economic planning based on realistic modest yields also contributed to the success of some of Jatropha projects in Mozambique and Malawi. Though Jatropha grows well under semi-arid conditions, higher seed yields are obtained if the plant has adequate water and nutrients (Ariza- Montobbio and Lele, 2010; Romijn, 2010), a finding which contradicts the general perception that Jatropha is a suitable agrofuel for semi-arid areas of Africa. Similarly, an economic analysis of Jatropha projects in India also showed that the net returns from Jatropha investment projects were negative because of low yields, and 30% of the farmers had already removed the trees from their farms (Ariza-Montobbio and Lele, 2010).

< Table 3: Summary of the results on literature review on sustainability of Jatropha biofuels in southern Africa >

Sustainability Indicators	**Impacts on Sustainability**	**Source**
Macro-economic impacts	These studies revealed that Jatropha outgrower contract farming had +ve impacts on GDP. Economic growth of Jatropha projects is estimated to have a poverty-growth elascticity of - 0.43; lower than those of conventional crops	Boccanfuso et al. (2013); Arndt et al., (2009); Ewing and Msangi, (2009)
Economic viability	Jatropha projects in SA are associated with – ve or marginally + ve NPV. The NPV is +ve only when family labour is used. Most of Jatropha projects collapsed in SA, especially large-scale projects.	Wahl et al. (2009); Von Maltitz et al., (2014); Romijn et al., (2014)
Access to land	Impacts of large biofuel biofuel plantations in SA is +ve. When most of the projects collapsed, the land was not returned to the local communities. However, smallholder out grower projects did not have adverse impacts on access to land as land rights were not transferred to investors.	Robeiro and Matavel, (2009); Romijn et al., (2014); Vermuulen and Cotula (2010).
Food security	Impacts on food security are –ve due to displacement of food crops. Farm workers perceived the impact of their involvement in Jatropha projects to have +ve impacts on food security.	Gasparatos et al. (2015); Kalinda et al., (2015); Van Eijk, (2015)
Biodiversity	Large scale Jatropha projects resulted in –ve impacts on biodiversity in SA; cultivation of Jatropha resulted in	Van Eijk et al. (2015a); Negussie; Negussie et al., (2015b).

	removal of natural vegetation. There are perceived –ve impacts of Jatropha invasiveness in SA.	
Water resources	Jatropha does not demand a lot of water as a result of high efficiency transpiration, but needs it needs irrigation to produce high yields even in rainfall regimes of 800 mm to 1 4000 mm/year.	Robeiro and Matavel, (2009); Rao et al., (2012)
Energy balance	LCA’s of Jatropha biofuels have net energy gains with EROIs of more than 1. In West Africa, EROIs values of 1.8 to 4.7 were estimated, indicating that Jatropha projects can make a +ve contribution to energy security.	Gasparatos et al. (2015); Ndong et al., (2009); Eston et al., (2013).
Climate change	Jatropha projects result in +ve impacts on climate mitigation when wastelands or degraded lands are used to cultivate Jatropha. There are –ve impacts in the form of high carbon debts when it was assumed there was land-use change resulting from the cultivation of the biofuel crop.	Gasparatos et al. (2011; 2014); Romijn (2011); Ndong et al., (2009); Achten et al., (2015); Searchinger et al., (2008).

Jatropha projects have also resulted in negative impacts on access to land in southern Africa. However, their impacts on food security and rural livelihoods have varied from positive to negative, depending on the type of business models and management practices adopted by projects. Large-scale projects tended to have more negative impacts on access to land, particularly when the projects collapsed as the land rights were often not transferred back to the local communities (Table 3). Case studies of biofuel projects in Mozambique have shown that even though employment in Jatropha farms reduced their labour-time for food production, the workers still perceived the projects to have improved their food security. This could be attributed to limited income generating opportunities as is the case in other rural areas of southern Africa, where employment by biofuel plantations and similar livelihood activities serve as reliable sources of income (Gasparatos et al., 2015). However, Jatropha cultivation is associated with adverse impacts on food security when it displaces conventional crops.

The impacts of biofuel projects on climate change mitigation in sub-Saharan Africa and in southern Africa in particular, were found to be positive when it was assumed that Jatropha was grown on degraded lands or wastelands, but negative when it was assumed land-use change occurred as a result of the cultivation of the biofuel crop (Tables 2 and 3). These studies have also shown that land-use change contributes to negative GHGs balances, resulting in carbon debts requiring long repayment periods. Related to the impact of biofuels on GHG balances is the contribution of biofuels to energy security. Jatropha biofuels in sub-Saharan Africa have the potential to make a positive contribution to the goal of energy security since they have net energy gains, with positive values of EROIs greater than one. However, the main concern is that the EROIs of Jatropha biofuels are lower than those of other biofuels such as sugarcane bioethanol, which have values of up to 9, whereas values of fossil fuels are even much higher, estimated to reach 15 to 20 (Gasparatos et al., 2015).

The foregoing offers lessons for energy policy in Botswana. Firstly, it is necessary for the Government of Botswana to formulate appropriate and comprehensive policies for biofuel development. For instance, the Government could consider providing support to certain types of biofuel projects at their early stage of development. The specific policies and regulations could, *inter alia*, include tax rebates, subsidies, pricing policy for biofuels, blending mandates, and indicative targets for biofuel consumption in the transport sector (Schut et al., 2010; Dufey, 2006). Though there are environmental benefits associated with biofuels, several countries in southern Africa still subsidise fossil fuels as the case study of Zambia has demonstrated (Gasparatos et al., 2015). The learning curve of the Brazilian Alcohol Programme (PROALCOOL), introduced in 1975 to promote substitution of gasoline with bioethanol, demonstrated that the unit cost of the production of a biofuel could be reduced when the experience of running the project increases, suggesting that biofuel projects in Botswana may not necessarily require subsidies in the long run (Goldenberg et al., 2003).

Secondly, the large plantation business model of biofuels should be discouraged in Botswana, it is associated with very high production costs and low financial returns due to low yields of the Jatropha crop; a crop which is not yet fully scientifically researched. The Jatropha out-grower contract farming model seems to be an appropriate model for biodiesel production in Botswana due to its lower adverse impacts on environmental sustainability, and its stronger pro-poor development impacts (Gasparatos et al., 2015; van Eijck etal., 2014). Botswana's on-going research on new Jatropha biofuels has the development of new Jatropha as one of its goals. The stakeholder questionnaire interviews revealed that the progress of this research is slow due to challenges such as severe winters which hinder fruit formation of Jatropha trees, water shortage and adverse effects of heat waves (Kgathi et al., 2016). There is need to consider these challenges when planning commercial cultivation of this crop.

Thirdly, the failure to return the land rights to the local communities after the biofuel projects have collapsed needs to be addressed due to its implications for distributive justice, procedural justice and the rights of people to self- determination as clearly articulated by Vermuulen and Cotula (2010). There is a need to introduce legal safeguards for the protection of the land rights of local communities in Botswana in order to ensure that they do not lose their land rights in the future when biofuel projects collapse as was the case in Tanzania. However, it is unlikely that the large-scale business model will be adopted in Botswana due to the semi-arid conditions of the country. If this model is adopted, it will be necessary to lease the land for the production of biofuel crops to foreign investors. This land, which will be registered under customary tenure, will need to be converted to common law in order to obtain a lease from the Department of Lands (Dikobe, 2016). In the event the biofuel project collapses, the foreign investor will continue to own the lease until it expires, after which the land will remain the property of the Department of Lands. To safeguard the rights of local communities, it is recommended that the Department of Lands should promote the issuing of leases to joint ventures of local communities with foreign investors. This approach will ensure that when the project collapses or when the foreign investor leaves, the local communities will continue to have rights to the land.

Lastly, an attempt should be made to ensure that land-use change and high carbon debts are minimized as they have adverse impacts on climate change and biodiversity. Achten et al (2013) suggest that these carbon debts should be as small as possible if biofuel development is to be considered an effective strategy for climate change mitigation. This view is consistent with our criterion of meso-sustainability discussed in section 2, which tries to ensure, by suggesting the limits of use, that depletion rates and thresholds of environmental degradation of ecosystem services are not exceeded (Hardi, 2007). High carbon debts should be avoided by reducing land conversion of naturally vegetated land and by using existing agricultural lands or wastelands for cultivation of Jatropha biofuels. The use of agricultural lands may, however, result in adverse impacts on food security as food crops may be displaced, whereas wastelands could be associated with low yields if new Jatropha varieties are not available. Policy-makers should therefore be made aware of this trade-off in order make the right decisions.

9.0 Conclusion

The results of this paper suggest that Jatropha biofuel projects have not performed well economically in southern Africa, mainly due to lack of economic viability of its projects as a result of low seed yields of the Jatropha plant, which is still wild and has not been improved through plant breeding. The perception that wastelands and degraded agricultural lands are viable for Jatropha production has been proved to be incorrect as the yields tend to be lower than expected due to insufficient water and soil nutrients. In response to this problem, the

Botswana Government is undertaking research on the development of new high yielding varieties.

The impacts of Jatropha biofuels on social sustainability in southern Africa were varied, ranging from negative to positive impacts. Though large-scale Jatropha projects tended to provide employment opportunities to farm workers in rural areas of southern Africa, they were characterised by negative impacts through the loss of land rights and displacement of food crops due to direct and indirect land-use change. These impacts may have negative effects on human welfare and may increase the vulnerability of rural households to shocks. Small-holder Jatropha projects tended to have more positive impacts on social sustainability, particularly when Jatropha was grown in hedgerows rather than as a monoculture.

Jatropha projects were found to be net-carbon sinks in southern Africa when it was assumed their cultivation was done on wastelands and degraded agricultural lands. When Jatropha projects are associated with conversion of woodlands or forests, they cause high GHG emissions due to land-use change which results in high carbon debts requiring many years to be repaid. There is also evidence that Jatropha projects would require more rainfall than expected, suggesting that irrigation might be required in semi-arid Botswana. In addition, Jatropha biofuels, especially large-scale plantations are associated with adverse impacts on biodiversity since natural vegetation is usually removed when cultivating the crop. While there is no evidence of Jatropha invasiveness in southern Africa, additional research is required to investigate this issue.

In summary, it is recommended that Botswana should continue to undertake research on the development of new high yielding Jatropha varieties as they seem to be an answer to the problem of negative economic sustainability. In addition, appropriate policies and legislation for the management of Jatropha should be introduced and the experience of countries such as Brazil, successful in biofuel development, should serve as a benchmark. Finally, an attempt should be made to ensure that all Jatropha biofuel projects are piloted before they are implemented in order to test their economic viability

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