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thesis entitled

SUSTAINABILITY OF JATROPHA CULTIVATION FOR
BIODIESEL FUELS

presented by

Paramjeet Pati

has been accepted towards fulfillment
of the requirements for the

M.S. degree in Environmental Engineering

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SUSTAINABILITY OF JATROPHA CULTIVATION FOR BIODIESEL FUELS

By

Paramjeet Pati

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Environmental Engineering

2010

ABSTRACT

SUSTAINABILITY OF JATROPHA CULTIVATION FOR BIODIESEL FUELS

By

Paramjeet Pati

The depletion of fossil fuel reserves and increases in oil prices have resulted in the quest for the ideal biofuel feedstock. With corn-based ethanol contributing to increased food prices, non-edible vegetable oil-seed plants (e.g., jatropha) and second-generation alternatives (e.g., switchgrass and algae) are being explored as potential feedstocks for biofuels. Biofuels provide a renewable alternative to fossil fuels and have several potential benefits; environmental as well as societal. However, there are concerns about the long-term sustainability of biofuels. This thesis discusses some of the major concerns about the lifecycle behaviour and the water footprint of jatropha-based biodiesel, while also addressing the socio-economic impacts, the ethical issues and the overall sustainability of biofuels in general.

"…You can't always get what you want

But if you try sometimes you might find

You get what you need…"

-The Rolling Stones

ACKNOWLEDGEMENTS

I believe that my Masters thesis is integrally linked with my overall M.S. experience. I would like to express my heartfelt gratitude to the people who made this journey possible.

I will start by thanking **Mr. Dennis Seybert** and **Mr. Eric Christensen** from the University Printing Services, where I worked during my first year at MSU.
Dennis: I owe you my gratitude for giving me my first job in the United States. Thank you for being patient with my mistakes.
Eric: You were the nicest supervisor and were always kind and fair to me. Thank you.

I shall remain indebted to **Dr. Susan Masten**, **Dr. Syed Hashsham,** and my thesis committee members **Dr. Melvin Yokoyama** and **Dr. Irene Xagoraraki** for their valuable inputs, constant support and encouragement.

There are great advisors. Above that, there are *awesome* advisors, after which, there's a huge gap. And then there's my advisor - Dr. Susan Masten.
Dr. Masten: I can never thank you enough for what you have done for me. But I will say this: There are moments in life when we see a reason behind all the madness, chaos and turmoil – moments when disjointed events seem to connect as if that Invisible Hand is joining the dots of life and showing us a pattern, a path. These are moments are rare and fleeting, but when they occur, life just

makes sense. Looking back at the last two years at MSU, I experienced one such moment on the 31st of October 2008 (Friday, my first Halloween in the U.S.) at 9:20 am. That's when you agreed to be my advisor.

Dr. Yokoyama: This thesis would not have been possible without your invaluable inputs and guidance. Thank you for the samples, lab supplies and financial support for the research. I really appreciated the flexibility you allowed me throughout my research.

Dr. Xagoraraki: Thank you for your time and effort in reviewing my thesis draft. Your suggestion to focus on nanopartcles for the project report in ENE 890 helped me find my research interest for my PhD.

Dr. Hashsham: I am thankful for your advice and guidance during my initial days at MSU. Thanks for maintaining high expectations from me and for believing that I could meet them.

I must thank my fellow graduate students – **Alla Alpatova**, **Farhan Ahmad**, **Indumathy Jayamani**, **Prianca Bhaduri** and **Deric Patton** - for their help and support over the last two years.

Alla: From how to use the Parafilm, to successfully run the software for the HPLC setup – you taught me so much regarding lab work. Thanks for lending me those textbooks, for the innumerable free rides and shopping trips, homemade pizza and for teaching me a smattering of Ukrainian and Russian. You are one of the kindest persons I have ever met and it is an honour being your friend.

Bol`shoye spa`siba.

Farhan: I will remain ever grateful to you for all your help and suggestions. You helped me navigate my way through the initial days at MSU and were always there when I needed you. Thanks.

Indu: Thanks for your help with the coursework and for the troubleshooting tips for HPLC. You truly an 'idea-person'.

Prianca: Thank you for being a good friend. Thanks also for all the free food!

Deric: I owe you a huge "Thank you" for all your help in the courses throughout my Masters degree. Our project for CE 421 was the best 'team-experience' I have ever had. I could have never been the teaching assistant I was without your invaluable suggestions regarding CSE 101. Thanks for everything.

My research would not have been possible without the support from **Dr. Susan Hengemuehle** and **Mr. Pan Yanlyang**.

Sue: I walked into the lab with virtually no experience in research. You helped me take my first faltering, baby steps in laboratory work and taught me that research can indeed be fun. Thanks for having so much faith in me. Also, thanks for helping me print the final version of the thesis!

Pan: My laboratory work would not have been possible without all your help. Thanks for your patience while handling my unending stream of questions. I will always remain grateful for the hands-on laboratory skills I have learnt from you.

I would like to thank our graduate secretary (Environmental Engineering) **Ms. Lori Larner**: Thank you for managing all my paperwork, ordering lab supplies and helping me handle the two gadgets in ERC that I could never get to work – the telephone and the printer. Lori, you are the best!

I will always remain grateful to the Department of Civil and Environmental Engineering for the financial support in the form of the teaching assistantship, which, for me, was an absolute godsend.

I am also grateful to my parents and my family for their love and support. Most of all, I must thank my grandfather Dr. Keshab Chandra Pati for the habits taught early in life, which made me the person I am today.

Paramjeet Pati

25th March 2010

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Alternative sources of energy: The reemergence of biofuels[1]

In recent years, there has been much interest in the development of alternative energy sources. The depleting reserves of fossil fuels, the growing awareness of the negative environmental impacts of conventional fossil fuels (e.g., coal[2], petroleum[3]), and the geopolitical pressures to reduce the dependence on imported fuel are the main driving forces behind the search for clean and renewable sources of energy. Examples of alternative energy include wind (windmills), solar (photovoltaic cells) and water (hydroelectricity). Apart from these sources, biodiesel[4] has received considerable attention as another promising source of renewable energy (Murugesan et al. 2009, Ma and Hanna 1999, Raneses et al. 1999).

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[1] Giampietro et al. (1997) defined biofuel as "any type of liquid or gaseous fuel that can be produced from biomass substrates and that can be used as a (partial) substitute for fossil fuels. Biodiesel, ethanol, methanol are subcategories of biofuels.

[2] Coal mining has come under severe scrutiny due to its negative environmental impacts. Palmer et al. (2010) described mountain top mining with valley fills (MTM/VF) as "surface mining operations that remove coal seams running through a mountain, ridge, or hill; it may also refer more broadly to large-scale surface mining, including area or contour mining in steep terrain that disposes of excess rock in heads of hollows or valleys with streams". In mountain top mining of coal, the upper elevation forests are cleared and stripped of the topsoil. The buried coal is accessed by blowing up the underlying rocks using explosives. As a result, streams in the adjacent valleys get buried by the debris (mine "spoil"). Surrounding ecosystems are severely affected, resulting in habitat loss, soil erosion and irreversible damage to terrestrial and aquatic life.

[3] Oil fires in petroleum mining and refinery processes release harmful particulate emissions, in addition to greenhouse gases. Oil spills in natural water bodies cause severe damage to aquatic flora and fauna.

[4] The National Biodiesel Board (NBB) defined biodiesel and biodiesel blend as follows:
Biodiesel, n - a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100, and meeting the requirements of ASTM D 6751.
Biodiesel Blend, n—a blend of biodiesel fuel meeting ASTM D 6751 with petroleum-based diesel fuel, designated BXX, where XX represents the volume percentage of biodiesel fuel in the blend. [1]

However, biodiesel is not a *new* alternative to fossil fuels. Olive oil was used for lighting lamps during the time of the Patriarchs (1950 – 1500 BCE) [1, 156]. Before the discovery of petroleum by Edwin Drake in 1859, ethanol[5] was used as a fuel (Kovarik 1998). Vegetable oils (castor, peanut), animal oils (whale oil, tallow from beef or pork), refined turpentine, wood alcohol (methanol) and grain alcohol (ethanol) were used as lamp oils in the United States and Europe in the nineteenth and twentieth centuries. Samuel Morey invented the internal combustion engine (patented in 1826), which ran on a "mixture of steam and the vapour of heated turpentine" (Hodgson 1961). In 1860, German inventor Nicholas Otto invented the four-stroke internal combustion engine that was fuelled by ethanol (Solomon, Barnes and Halvorsen 2007). In 1896, Henry Ford built his first automobile (the quadricycle) to run on pure ethanol. In 1900, at the World Exhibition in Paris, Rudolf Diesel[6] demonstrated his first engine that ran on peanut oil (Shay 1993). Later, in 1908, Ford built the Model T automobile[7] that could run on ethanol, gasoline or a combination of both (Antoni, Zverlov and Schwarz 2007).

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[5] Structurally, ethanol obtained from plant sugars (obtained by fermentation) is different from biodiesel, which is essentially a mixture of mono-alkyl esters (obtained by transesterification).

[6] In his paper "*Historical perspectives on vegetable-oil based diesel fuels*", Knothe mentioned that the idea to use peanut oil might not have been Diesel's own idea. According to Knothe, Diesel used peanut oil in his engine's demonstration at the Exposition Universalle (1900, Paris) at the request of the French government, which wanted to test the applicability of Arachide (earth nut or pea nut) oil. (Arachide grew plentifully in the French-occupied African colonies and was a possible alternative to imported coal or oil.) (Knothe, 2001)

[7] This was the first 'flexible fuel vehicle' (FFV) invented (Keeney (2009). The hybrid vehicles and 'flex-cars' of today derive the idea of using biodiesel blends from the Model T automobile.

When the Union Congress imposed a \$2.08 $gallon^{-1}$ alcohol tax in 1862 (Mosher and Beauchamp 1983) during the Civil War (1861 - 1865), ethanol-based biofuel could no longer compete with gasoline[8]. Although ethanol was used to fuel many domestic army vehicles during World War II (Keeney 2009), biofuels were not considered as a serious substitute for gasoline. While interest in biofuels waxed and waned in the years that followed, the shockingly great increase in oil prices[9] during the Arab oil embargo (1973) caused the reemergence of biofuels as a domestic and renewable source of energy (Songstad et al. 2009, Shihata 1974). The search for "green" fuels received further impetus as the health and environmental effects of gasoline additives (TEL[10], and later, MTBE) came to light. Ethanol made a major comeback as a fuel additive in 2000 after the use of MTBE[11] as a fuel oxygenate was banned (Szklo, Schaeffer and Delgado 2007).

At present, ethanol can be obtained from starch- and sugar-based feedstocks (e.g., corn, maize) or cellulosic feedstocks (plant biomass such as stalks, leaves, trunks, branches, and husks). Biofuel can also be produced from edible

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[8] Later, in 1906, President Theodore Roosevelt repealed the tax (Carolan, 2009). However, this failed to revive the ethanol industry completely, because by then gasoline was the accepted fuel in automobile engines.

[9] In 1973, the average price of a barrel of oil was \$2.70 and the average cost of gasoline at the pump was about 35¢ a gallon. By March 1974 oil prices had climbed to nearly \$12 a barrel (nearly 330% increase). Gasoline prices increased to 86¢ per gallon by 1979, and \$1.19 a gallon by 1980 (Commoner, 1979)

[10] The toxicity of tetraethyl lead (TEL) was suspected as early as 1922. The US Environmental Protection Agency (EPA) began to phase out leaded gasoline in 1975, which was deemed successful by 1986 (US EPA).

[11] Methyl tertiary-butyl ether (MTBE) is suspected to be a human carcinogen. Groundwater contamination from MTBE due to gasoline leaks and spills is suspected in at least 29 states in the United States (US EPA).

vegetable oils (e.g., soybean and sunflower). However, there are concerns regarding the use of food crops (e.g., maize, corn and sugarcane) for biofuel production. With a growing world population, there is an increasing demand for food and a pressing need to reduce food prices. On the other hand, there is also an urgent call to produce more biofuels and to reduce the dependency on imported oil. Biofuels would help bolster the national economy, mitigate the environmental impacts of fossil fuels and fight global climate change by reducing the emission of greenhouse gases (GHGs). In this context, 'non-food-based' feedstocks[12] for biofuels can provide an alternative for biorenewable energy while simultaneously mitigating food-insecurities across the world. *Jatropha curcas*[13], a non-edible oil seed plant, has been proposed as a potential

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[12] Biofuels produced from non-food based feedstock are classified as second-generation biofuels while those produced from food crops (e.g., cereals, sugar crops and oil seeds) are classified as first-generation biofuels.
Examples of second-generation biofuel feedstock include ligno-cellulosic plant byproducts (e.g., cereal straw, corn stalk, sugar cane bagasse, rice husks), non-edible whole plant biomass (e.g., grasses, plants or trees grown for energy only), organic components of municipal solid wastes and byproducts from animal fat processing industry, microalgae etc.
At present, technologies for biofuel production from second-generation biofuels (e.g., biofuel from microalgae) are still in their infancy and the feasibility of large-scale biofuel production from newer second-generation technologies is yet to be proved.

[13] In the report *"From 1st Generation to 2nd Generation Biofuel Technologies"*, (by the International Energy Agency (IEA), www.iea.org) *Jatropha curcas* has been classified as a second-generation biofuel feedstock.
Jatropha biodiesel is a vegetable oil based product similar to the biofuel produced from palm oil or canola oil. I believe that jatropha should be classified as a first generation biofuel feedstock because of the non-toxic, edible varieties of jatropha found in Mexico. Moreover, the classification of biofuels as first or second generation should also take into account the difference in the technologies used for the production of biofuels. At present, biofuel production from jatropha involves transesterification of raw oil. The technology (i.e., transesterification) therefore is no different from that used for producing biodiesel from other vegetable oils (e.g., sunflower or soybean).
The United Nations Conference on Trade and Development (UNCTD) has classified jatropha as a first generation biofuel feedstock in the report "Biofuel production technologies: status, prospects and implications for trade and development" (Larson, 2008).

feedstock for sustainable production of biodiesel (Achten et al. 2008, Foidl et al. 1996, Francis, Edinger and Becker 2005, Ye et al. 2009).

Jatropha curcas belongs to the Euphorbiaceae (pronounced yoo-for-bee-ay-see-eye) plant family. It is a drought-resistant, oil-bearing shrub that is well adapted for a variety of soils in tropical and semi-arid conditions, and has been referred to as an "all purpose, zero waste perennial plant" (Verma and Gaur 2009). It is widely distributed in the wild or semi-cultivated areas in Central and South America, Africa, India and South East Asia. Jatropha can grow under a wide range of rainfall regimes from 200 to over 1500 mm per annum. In low rainfall areas and in prolonged rainless periods, the plant sheds its leaves to conserve moisture (Openshaw 2000). As its fruit, leaves and stems have several toxins and antinutritional components[14], the plant cannot be used as a feedstock for animals and is therefore used as a living fence to restrict farm animals from grazing land (Heller 1996, Gubitz, Mittelbach and Trabi 1999, Aderibigbe et al. 1997). Various parts of the plant have medicinal value and antimicrobial properties. Also, like all trees, it fixes atmospheric carbon, stores it as biomass and assists in the build up of soil carbon, thereby acting as a carbon sink. Jatropha can grow on marginal[15] soils in semi-arid areas, improve the soil

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[14] As mentioned before, non-toxic varieties of the plant are found in Mexico.

[15] *A note on 'marginal' lands:* One of the factors mentioned in favour of jatropha is that it grows on degraded lands in semi-arid conditions. In the literature, the term 'marginal' is widely used to refer to these lands. Gressel (2008) mentioned that such lands are 'marginal' only in the economic sense and the term should be used in its proper context. The lands that have the least economic value are categorized as marginal lands . This implies that the economic output from such lands is less than the expected outputs from jatropha cultivation and biofuel production. However, before allocating such lands for jatropha cultivation, the social and environmental impacts should be carefully considered. Questions about the

structure, prevent soil erosion in degraded areas and help in land reclamation (Ogunwole et al. 2008). Achten et al. (2008) estimated the average oil content in jatropha seeds to be 34.4% (on a mass basis). The raw jatropha oil can be converted to biodiesel by transesterification. In recent years, jatropha has been in the news due to its potential as a 'low input' biofuel feedstock. Jatropha based biofuel programmes are already being implemented in India, Indonesia, China and Africa.

However, there are several uncertainties regarding the yield, water footprint and the overall sustainability of jatropha, which must be addressed before cultivating the plant on a large scale. Several issues related to the lifecycle behaviour and the water requirements of jatropha (and biofuels in general) are discussed in the chapters that follow. The socio-economic impacts of biofuels and the food-biofuel conflict are also addressed. Lastly, recommendations are made for promoting sustainable biofuel programmes and utilizing the potential environmental and societal benefits of biofuels.

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possible increased use of water, the need for irrigation and fertilizers, the cost of transportation from the marginal sites to the processing plants should be factored into the equation before approving large scale plantations in such 'marginal' lands.

Lifecycle Assessment (LCA):

Biofuels have been proposed as 'environmentally-friendly' alternatives to conventional fossil fuels (e.g., Ragauskas et al. 2006, Sanderson et al. 2006, Powlson, Riche and Shield 2005). However, several researchers have questioned the sustainability of biofuels (e.g., Searchinger et al. 2008, Hill et al. 2006, Scharlemann and Laurance 2008, Pimentel and Patzek 2006). The combustion of fossil fuels emits GHGs, which are considered to be responsible for global warming (Anderson, Hayhoe and Liang 2010). While the combustion of biofuels also emits GHGs, the plant biomass (i.e., biofuel feedstock) can reabsorb CO_2 during photosynthesis. Theoretically, the net CO_2 flux into the atmosphere may be negative (i.e., more carbon dioxide is absorbed by the biomass than released into the atmosphere by the combustion of biofuels), positive (i.e, there is a net CO_2 flux into the atmosphere) or zero (in the scenario when the biofuel is 'carbon neutral'[16]). If the net CO_2 flux is positive but less than that for fossil fuels, then biofuels are considered to be a 'greener' alternative to fossil fuels due to the reduced global warming effect. A major area of uncertainty is the assessment of the net CO_2 flux during the "lifetime" of the biofuel. From the initial design and development to the end-of-life stage, every product has a 'footprint' due to the demands on resources and the environmental impacts. The demand on the available resources and the net effect on the environment must

16 In the case of carbon neutral biofuels, the CO_2 emissions by the combustion of the biofuel are equal to the CO_2 assimilated by the feedstock plant.

be quantified to assess the sustainability of any product. Lifecycle assessment (LCA) is a tool for comparing and quantifying the environmental impact of the 'product' under consideration (e.g., Rebitzer et al. 2004, Pennington et al. 2004).

This chapter provides an introduction to the concept of LCA followed by a discussion of some selected LCA studies on jatropha-based biodiesel. The chapter also covers the major areas of uncertainty in LCA studies, the problems associated with the comparative analysis of different LCA studies and estimating the sustainability[17] of the biofuels. Finally, some recommendations are made to improve the comparability of the results of LCA studies in the future. The sections of the discussion related to jatropha are also pertinent to biofuels in general.

In the United States, the methodology of LCA originated from the analytical schemes developed by Harry E. Teasley Jr.[18] in 1969[19] (Hunt and Franklin 1996). The term 'LCA' came into use in 1990. Until then, between 1970 and 1990, the term REPA – resource and energy profile analysis – was used for

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[17] Besides the GHG and energy balance, discussions of the sustainability of biofuels must also include other factors such as the water footprint and social impacts. The water footprint and the socio-economic impacts of biofuels are covered in the later chapters.

[18] In 1969, the Coca Cola Company was considering various options related to packaging of the beverage. The options included self-manufacturing beverage cans, using plastic bottles, refillable bottles or disposable containers. The environmental consequences of the manufacturing and the packaging process were also being considered. At that time, Teasley Jr. was managing the packaging functions of the company. To make a decision regarding the packaging options, he visualized a method to "quantify the energy, material and environmental consequences of the entire life cycle of a package from the extraction of raw materials to disposal". (Hunt and Franklin, 1996)
The concept of LCA originated from the work that followed.

[19] Hunt and Franklin (1996) mentioned that around the same time (i.e., 1996) similar concepts of environmental impact assessment and sustainability were being explored in Europe.

environmental lifecycle studies. Rebitzer et al. (2004) provided a comprehensive definition of LCA:

> "Life cycle assessment (LCA) is a methodological frame-work for estimating and assessing the environmental impacts attributable to the life cycle of a product, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise—and others."

Although the effects of a product on human health are included under the impact assessment phase in LCA, the socio-economic impacts of the product are peripheral to LCA studies, which primarily focus on the environmental impacts.

The emphasis on environmental impacts is also seen in the description of LCA by the Society of Environmental Toxicology and Chemistry (SETAC):

> "LCA [Life Cycle Assessments] address the environmental aspects and potential environmental impacts (e.g. resource use and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment and disposal (i.e. cradle-to-grave)." [12] [20]

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[20] In fact, it is mentioned on SETAC's website that while environmental impacts, ecological health, human health and resource depletion are covered under LCA studies, *"it does not address economic considerations or social effects"*.

The LCA process consists of the following main phases: definition of the goal and the scope of study, definition of lifecycle inventories (LCIs), lifecycle inventory analysis, impact assessment, and interpretation of the results. In the goal definition phase, the product and the processes involved are identified and clearly explained. Based on the scope of study, there can be large variations in the results of LCA studies on the same product. These variations are caused by the assumptions built into the following three components of LCA studies: the system boundaries, the LCIs and functional units.

The International Standards Organization (ISO) has defined the system boundary as the "interface between a product system and the environment or other product systems" (ISO 14040 section 3.17). For example, if all the processes in the biofuel production chain are included in the system, then the spatial boundaries may be defined by the acreage of land and the temporal boundaries would depend on the number of harvesting seasons or the carbon-debt payback period. Moreover, the system boundaries would also depend on the processes included in the system. For example, all the processes in the biofuel production (i.e., from the production of biofuel from the feedstock plant seed to the consumption of the final product - "from seed to wheel"[21]) may be included, or particular set of processes (e.g., the pre-harvesting processes) may be excluded. Thus, the

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[21] In the LCA studies involving fossil fuels, such an approach is known as "well-to-wheel" approach. If the system does not account for the emissions from the final product, then the approach is called the "well-to-tank" approach. When the production processes (e.g., drilling, refining etc.) of the fossil fuel are excluded, then the approach is known as "tank to wheel" approach.

choice of the system boundaries strongly depends on the scope of the LCA study.

Lifecycle inventories or LCIs are the components defining the system under consideration. If the GHG balance for biofuels is considered, then the LCIs can be: land (to account for the soil carbon lost during tillage), fertilizers, fossil fuels consumed in the various steps of biofuel production (operating the agricultural machinery, transport, production processes in the biofuel factory), and the final product[22]. Also, if fertilizers are excluded from the analysis, the system boundaries change accordingly. It is interesting to note this interdependence of the system boundaries and the LCIs. The interdependent nature of the system boundaries and the LCIs also underlines the complexities involved in LCA studies.

Besides the system boundaries and the LCIs, functional units also play a significant role in the final outcome of LCA studies. Functional units are a measure for quantifying and comparing the inputs and the outputs involved in any process. In LCA studies on biofuels, the two most commonly used functional units are GHG and energy (Davis, Anderson-Teixeira and DeLucia 2009). While GHG units are important for assessing the environmental impacts of biofuels, energy units help in estimating the 'amount' of biofuels needed to yield the same amount of energy as the fossil fuels that they replace. Several efficiency terms

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[22] Inventory impact assessment involves the quantification of these LCIs, besides GHG emissions and energy consumptions. The potential human and environmental impacts of the consumption of resources (e.g., energy, water, land) and the emissions identified in the inventory analysis are covered in the impact assessment phase of LCA studies. ('Life Cycle Assessment: Principles And Practice', US EPA)

(e.g., efficiencies of the processes for converting biomass into bioenergy, efficiencies of the machinery used in the various production stages etc.) are used to calculate the net GHG balance or the net energy value[23]. The assumptions built into these efficiencies contribute to the uncertainties and the differences in the final output of LCA studies. Despite the uncertainties, LCAs are widely used in evaluating the energy efficiencies, GHG emissions and the overall sustainability of biofuels.

A discussion of three selected LCA studies of jatropha by Gmunder et al. (2010), Ndong et al. (2009) and Prueksakorn and Gheewala (2008) follows next. The objective of the following section is to discuss the differences in the methodologies adopted for the LCA studies and the difficulties in comparing their results. This section does not attempt to provide a comprehensive review of LCA studies conducted on jatropha. These three studies have sharply different objectives and methodologies for selecting the various components of LCA (e.g., functional units, energy units, system boundaries etc.). While there are several LCA studies of jatropha (e.g., Reinhardt et al. 2007, Whitaker and Heath 2009, Dehue and Hettinga 2008, Lam, Lee and Abdul Rahman 2009), these three

[23] Dale (2007) mentioned that 'net energy' is an "irrelevant" and "fundamentally wrong" metric when comparing biofuels with fossil fuels. "Net energy is defined as ethanol's heating value (a fixed, known quantity) minus the fossil energy inputs required to produce the ethanol." The author said that the concept of 'net energy is flawed as it considers all energy inputs as equivalent, i.e., "one megajoule (MJ) of coal equals one MJ of petroleum equals one MJ of natural gas".
Although the energy values are same, the economic values are markedly different. Therefore, considering all energy inputs as equivalent regardless of their forms is misleading.
The author explains the discrepancy using the classic 'comparing-apples-with-oranges' phrase as follows: "Apples are good for making apple juice; apples are not good for making orange juice. Petroleum is uniquely suited for making liquid fuels; neither coal nor natural gas are nearly so well-suited to make liquid fuels. The net energy calculation includes coal, petroleum and natural gas. Thus it is misleading and irrelevant as a public policy guide to use net energy to compare liquid fuel alternatives."

studies are selected for discussion because a comparison between the three studies best demonstrates two things: 1) how the system boundaries, the functional units and the end results of LCA studies of the same product can vastly differ, based on the objectives of the studies 2) how the authors' subjectivity in the choice of the various components of LCA makes comparisons between LCA studies difficult.

First, the detailed methodologies and the results of the individual studies are presented, followed by a discussion of the underlying differences[24]. While there are several differences in the processes involved in the production chain, the following section focuses primarily on the differences in the components of LCA (e.g., functional units, energy units etc.). Lastly, the issues related to the land use change (LUC), carbon debt, soil carbon and carbon sequestration are discussed.

Gmunder et al. (2010) conducted an LCA on jatropha for rural electrification in Chhattisgarh, India. The authors used jatropha oil in a pilot power plant to generate electricity. The reference system was based on fossil diesel. The functional unit was chosen to be 1 kilowatt-hour of electrical energy. The system boundaries were based on "all relevant processes necessary for electricity generation, including transport and infrastructure". All processes from the cultivation of jatropha to the use of the final product were considered[25]. The

[24] A discussion on the LCA studies would be difficult without an understanding of the methodology involved. Therefore the methods of the individual studies are presented before the analysis of the differences in the LCA.

[25] Therefore, the approach may be likened to a 'well-to-wheel' approach.

study was based on young jatropha plants and a constant seed yield of "1 kg per tree over the whole lifespan of 50 years" was assumed. While the energy content of jatropha oil was used to allocate the energy value obtained, stoichiometry was used to allocate the carbon value for GHG calculation. The energy requirement was expressed as cumulative energy demand (CED), measured as MJ input per MJ output. The calculations excluded the environmental burden of the equipments' (e.g., the expeller) disposal[26]. The land use change (LUC) and the change in the soil carbon stock were not considered in this study. The saplings were planted at the start of the monsoon season. It is assumed that the rainfall in the monsoon season was sufficient for the plants' growth and no irrigation was necessary. During the first year, 4 g of diammonium phosphate (DAP) and 3 g solid compost per plant was used as fertilizer[27]. After the first year, neither fertilizers were applied nor were the plants irrigated. It was anticipated that 0.04 g of Chloropyrifos 20EC insecticide would be used per plant every five years[28]. The seeds were heated in a wood fired steam kettle to improve the oil extraction in the expeller. The seedcake was mixed with fresh seeds and run through the expeller once more to obtain an overall oil yield of 21% (by weight). The expeller and the generator in the pilot plant were run on jatropha oil. The authors did not

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[26] CED calculations involve accounting for all energy consumptions using a 'cradle-to-grave' approach. Typically, the energy requirements for disposal are included in CED calculations.

[27] The authors have not reported the total number of plants or the size of the plantation. Therefore the total amount of fertilizer added could not be estimated. The authors have mentioned that the saplings were "planted at the edge of fields and roads with a spacing of 2m × 2m per plant".

[28] At the time the article was written, the jatropha plantation was two years old.

mention if the same is true for the reciprocating pump that was used in the filtration step that followed the extraction.

The GHG emissions were 0.27 kg CO_2eq (KW-h)$^{-1}$ of electricity. 20.7%[29] of the total GHG emissions resulted from jatropha cultivation, while 79.3% of the emissions were attributed to the other steps involved in generating electricity from jatropha oil. The authors estimated that the global warming potential (GWP) of jatropha oil is six times lower than that of diesel and elaborated that the use of the jatropha oil for the generation of electricity can save 1.5 kg CO_2eq (KW-h)$^{-1}$ of electricity generated and reduce the GHG emission by seven times as compared to a diesel. The authors also estimated that considering the small input of fertilizers, the eutrophication effect from jatropha cultivation is anticipated to be was relatively large. (This eutrophication effect was not quantified in the report). The authors suggested using the seedcake as either fertilizer, feedstock for producing biogas or as briquettes for increased economic and energy returns.

Ndong et al. (2009) conducted an LCA study of jatropha in Western Africa, based on the well-to-tank approach (i.e., the GHG emissions from the combustion of the biodiesel were not considered). The functional unit was taken to be 1 MJ of jatropha methyl esters (JME) (the end product of the transesterification process). The CO_2 fixed by the plants during the lifecycle and the impacts of LUC were excluded from this study. The yield was assumed to be 4 tonnes of dry seeds ha^{-}

[29] All numbers are presented as in the original article.

^{1}[year^{-1}] in the 'baseline' scenario. The authors expressed the yield in "tonnes dry seeds ha^{-1}". Dry seed yields from jatropha are commonly reported to be 5 tonnes dry seeds ha^{-1}year^{-1}. From these values, it is assumed that the temporal boundary used in this study was one year.

The authors considered four other scenarios for jatropha biodiesel production, besides the baseline scenario. In scenario A, the yield was varied between 3 - 5 tonnes dry seeds ha^{-1}[year^{-1}]. In scenario B the effects of transportation of the oil on the GHG emissions and energy yield were considered. In scenario C, the energy needs of the manual labour involved in the cultivation process were taken into account. Scenario D involved the use of neat jatropha oil in stationary engines (i.e., the transesterification step was omitted). In the baseline scenario, the energy yield was calculated to be 4.7 (i.e., for each MJ of fossil fuel consumed, 4.7 MJ of JME energy was produced.) Transesterification was the most energy consuming stage in JME production, accounting for 61% of the life-cycle energy needs. The agricultural stage accounted for 52% of the GHG emissions, with 93% of those emissions resulting from the use of fertilizers. Transesterification contributed to 17% of the total emissions while 16% of the emissions were due to the combustion of the final product[30].

The high GHG emission from the use of fertilizers and pesticides is attributed to the large amount of energy required in the manufacture of these agrochemicals.

[30] It is not clear how 16% GHG emissions resulted from the combustion of the final product, as the system boundaries were based on a well-to-tank scheme.

The net GHG emission was 23.5 gCO_2eq per MJ of JME. The authors mentioned that the corresponding emission from conventional diesel fuel is 83.8 gCO_2eq per MJ of diesel. Thus, as per the LCA study, biodiesel production from jatropha resulted in 72% reduction in GHG emissions as compared to conventional diesel fuel.

The authors compared the four different scenarios mentioned earlier to conduct a sensitivity analysis and to estimate the effect of yield, transportation, manual labour and the end use of jatropha oil. In scenario A, GHG emissions increased by 17% and energy consumption increased by 4% for the yield of 3 tonnes dry seeds $ha^{-1}[year^{-1}]$. Using a yield data of 5 tonnes dry seeds $ha^{-1}[year^{-1}]$ resulted in a 10% reduction in GHG emissions and 2% reduction in energy consumption. In scenario B, the transportation of jatropha oil over a distance of 564 km by trucks increased the GHG emissions and energy needs by 8% and 14%, respectively, as compared to the transportation by freight train. In scenario C, including the energy cost of manual labour in the calculations, showed a 29% increase in the net energy requirements to produce 1 MJ of JME. In scenario D, the local use of neat jatropha oil increased the energy yield from 4.7 to 26.4[31] (compared to the baseline scenario) and increased GHG savings from 72% to 85% (compared to conventional diesel).

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[31] The authors have considered that neat jatropha oil may be locally used as "fuel for fueling pumps, mills or small-scale power production". However, they do mention that using neat vegetable oils would require modifications in the engines.

Prueksakorn and Gheewala (2008) conducted a lifecycle "energy balance" of jatropha-based biodiesel in Thailand. GHG emissions and LUC were not considered in this study. The authors based all calculations on the cultivation of jatropha on one hectare of land for twenty years. In this study, the use of diesel[32] for the preparation of land, the inputs for irrigation[33] and the use of fertilizers[34] were taken into account. Energy requirements for manual labour were excluded from the study. Considering various scenarios of yield, fertilizer requirement and other factors in the process chain, the authors calculated the net energy ratio (NER) for jatropha biodiesel to range from 0.53 to 2.70 if the byproducts (seedcake, wood etc.) are not used for fuel. Using the byproducts as fuel yielded an NER range of 1.93–11.99. The average biodiesel yield from jatropha best-case scenario was calculated to be 2.7 ton ha^{-1} $year^{-1}$. The sensitivity analysis showed the NER to be most sensitive to changes in co-products yield. A 10% change in co-products yield resulted in a change in the NER by about 8%.

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[32] Diesel use for land preparation (ploughing, furrowing etc.) for jatropha cultivation was estimated to be 25–40 L/time/ha [L $time^{-1}$ ha^{-1}].

[33] The irrigation requirements have been reported as follows: "time of irrigation ≈ 12.5 h/ha/time [h $time^{-1}$ ha^{-1}], frequency of irrigation ≈ 15 day/time [day $time^{-1}$] for dry season only, and rate of diesel consumption ≈ 0.63 L/hour [L h^{-1}]".

[34] The fertilizer requirements reported in the study are unclear. The authors have used two estimates for the fertilizers requirements. For the worst case scenario ("poor land"), using data from the literature, the NPK fertilizer requirements (N:P:K 40:20:10) were estimated to be: 160 kg for the first year, 25.5 kg for the second year, 63 kg for the third year, 126 kg for the fourth year, 252 kg for the fifth year and 378 kg for the sixth year. The authors have reported this as: "The amount of chemical fertilizer for years 1, 2, 3, 4, 5, 6, and onward is 160, 25.5, 63, 126, 252, 378, and 378 kg of N:P:K (40:20:10), respectively." At the same time, the authors have also mentioned that "[f]rom second year to 20th year of plantation, JCL [*Jatropha curcas* L.] seedcake is used instead of chemical fertilizers."
For the best case scenario, (fertile land), the authors have estimated that 312.5 kg of NPK fertilizer (N:P:K 15:15:15) was used per year.

There are several differences in the methodologies of the three LCA studies. While Gmunder et al. (2010) used 1 kilowatt-hour of electrical energy as the functional unit, Ndong et al. (2009) used 1 MJ of energy from JME. Prueksakorn and Gheewala (2008) based all calculations on the cultivation of jatropha on one hectare of land for 20 years. The choice of the functional units seems to be strongly dependent on the system under consideration as well as the objective of the study. Reinhardt et al. (2007) mentioned, "Depending on the questions to be answered, different functional units might be necessary." In fact, in their studies of the lifecycle analysis of jatropha, Reinhardt et al. (2007) used the yield of jatropha fruit from one hectare of land in one year as the functional unit because in their studies, "most questions [were] relate[d] to land use efficiency". Achten et al.[35] used '100km driven with a 4×4 pick up' as the functional unit in their LCA studies of jatropha. Since jatropha based biodiesel will be used to replace fossil fuels, the most appropriate functional units would be those that relate the services obtained (e.g., distance travelled, electricity generated, energy obtained) or the environmental impacts (GHG emissions, eutrophication) to the unit consumption of biodiesel and fossil fuel. Such functional units will help in making comparative LCA studies. The complexity involved in the choice of the functional unit is seen in the following example. Keeping the transportation sector in mind, the distance travelled per unit of fuel may be an appropriate baseline to compare

[35] The year and the details of this publication could not be found. The abstract of this article can be accessed at: http://www.biw.kuleuven.be/lbh/lbnl/forecoman/pdf/Abstracts/Achten/Achten%20abstract%20poster%20gotheborg.pdf

the efficiencies of biodiesel and fossil fuel. The functional unit 'distance travelled per litre of biodiesel' may seem to be useful in comparing the energy efficiency and GHG emissions of biodiesel with that of the fossil fuel it would replace. In that respect, the functional unit used by Achten et al.[36] seems most appropriate[37]. However, based on the engine's efficiency assumed in such calculations, there would be inconsistencies in the final results. Hence, there is an urgent need to standardize the procedure for selecting functional units as they provide a baseline for comparing the lifecycle behaviour of biofuels.

The inconsistencies in the energy units used in LCA studies also make comparing different studies difficult. Gmunder et al. (2010) expressed the energy requirements as cumulative energy demand (CED), measured as MJ input per MJ output. Ndong et al. (2009) expressed the energy requirements in term of energy yield (i.e., fossil fuel energy consumed to produce unit energy of biodiesel), which is similar to the net energy ratio (NER) used by Prueksakorn and Gheewala (2008). CED and NER are different metrics and results expressed in terms of these units are difficult to compare.

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[36] 100km driven with a 4×4 pick up

[37] Runge and Senauer (2007) have suggested "greenhouse gas emissions per mile driven" to be used for evaluating the environmental impacts of biofuels.

The sum of all energy inputs in the entire lifetime (production, usage and disposal stages) of a product is called the Cumulative Energy Demand[38] of that product. Huijbregts et al. (2010) described the total CED as: "The total CED is composed of the fossil cumulative energy demand (i.e., from hard coal, lignite, peat, natural gas, and crude oil) and the CED of nuclear, biomass, water, wind, and solar energy in the life cycle." Thus CED is a 'cradle to grave' approach to energy accounting. In case of NER, the energy requirement depends on the system boundaries and whether the approach to energy accounting is 'well-to-tank, 'tank-to-wheel' or 'well-to-wheel'. Based on the system boundaries, the energy related to the auxiliary materials may be either included or excluded, whereas in case of CED, all the raw materials and auxiliary inputs related to the product are included in the calculations. (Gmunder et al. (2010) excluded the energy associated with the disposal of equipments.) Moreover, as mentioned earlier, the idea of treating different forms of energy as the same (i.e., equating 1 MJ of petroleum to 1 MJ of coal) while accounting for energy requirements seems flawed.

The yields from jatropha are another area of uncertainty in most studies. Francis et al. (2005) reported that depending upon soil type, nutrient availability and rainfall conditions, the seed yield for jatropha varies from 0.5 tons ha^{-1} $year^{-1}$ to

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38 Rohrlich et al. (2000) have explained the concept of CED as follows: "The life cycle of a product can generally be subdivided into the three phases of 'production' (P), 'use' (U) and 'disposal' (D) in which final energies, e.g. electricity or fuel, are engaged."
"Beside the direct energy input for production, use and disposal of a product, production facilities, as well as raw materials, auxiliary materials and consumables are also used. These are products which need energy for their own production process. The total of all energy inputs, concerning the consumption of primary energy, is called the Cumulative Energy Demand of a product."

12 tons ha^{-1} $year^{-1}$. Therefore the calculations for GHG emissions and the energy requirements will differ significantly based on the assumed values of yield. There are further complications with estimating the yield when other factors, e.g., the maturity of the plants, soil type, irrigation inputs, the use of fertilizers, the extraction efficiencies and the transesterification efficiencies are taken into account. Yields also play a significant role in estimating the water footprint[39] of jatropha.

As seen from the studies, transesterification is the most energy consuming stage in jatropha biodiesel production and the use of fertilizers has the maximum contribution to GHG emissions. It important to minimize the use of chemical fertilizers in jatropha cultivation as it significantly diminishes the GHG savings. However, as jatropha does not fix nitrogen, fertilizers will be necessary to replenish the lost nutrients (especially, nitrogen). Intercropping of jatropha with other crops, especially leguminous plants, may be a solution[40]. Noting the toxicity of jatropha, Benge (2006) has mentioned, “Closely spaced, Jatropha would eliminate grasses and shrubs on which livestock feed”, which suggests that there might be difficulties with intercropping other plants with jatropha. Genetic modifications for the suppression of the toxins can make it possible to intercrop legumes with jatropha, thereby minimizing the need for fertilizers.

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[39] The water footprint of biofuels is discussed in the next chapter.

[40] The Lao Institute of Renewable Energy (LIRE) has experimented with intercropping of papaya, ground nut, red and green peppers, tomatoes, and water melon with jatropha. [9]

Other factors that contribute to differences in the results of LCA studies are the assumptions regarding transportation and the decentralized[41] or centralized[42] nature of the production facilities. The two factors are interrelated and site-specific. The GHG emissions for transportation by truck would be more than that by trains, due to the lower load capacity of trucks. Therefore, the existing infrastructure for transportation must be efficiently utilized and the production facilities should be sited accordingly. Also, the local use of raw jatropha oil offers the dual advantage of GHG savings due to minimized transportation and energy savings by avoiding transesterification. Thus, the end use of jatropha oil has significant effects on the GHG- and energy-balance.

An important factor that was not considered in the three studies mentioned earlier is the land use change (LUC) and its impacts. I believe that LUC is integrally related to the concept of carbon debt, soil carbon content and the temporal boundary of the life cycle assessment. The major impacts of LUC are

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41 Decentralised systems: In decentralised systems of biofuel manufacture, all the production facilities are located close to the plantations. The extraction and transesterification are usually accomplished in small-scale plants. The raw oil is obtained by mechanical extraction and refined and either used directly or transesterified to obtain jatropha biodiesel. The main byproducts in decentralized systems are husks, seed cake (with residual oil) and glycerin (used for soap).

42 Centralised systems: Centralised systems are large-scale plants requiring larger amounts of feedstock, which are transported over greater distances as compared to decentralized systems. Thus transportation costs and the contribution to GHG emissions due to transportation are higher for centralized systems. In such systems, mechanical extraction can be followed by solvent extraction. This results in higher oil yields and lower specific energy inputs. Due to the additional solvent extraction step, the residual oil content in the seed cake is very low.
Reinhardt et al. (2007) have reported that centralized systems offer environmental advantages due to lower GHG emissions and lower specific energy requirements. The authors also mention that decentralized systems are promising in terms of socio-economic development of the region and might prove beneficial for sustainable development despite the lower environmental benefits.

deforestation, “carbon debt”, soil degradation[43], the migration and resettlement of the local population (forced or otherwise) and the competition with food crops for resources. LUC may involve altering natural ecosystems either for the cultivation of the biofuel feedstock or the crops displaced by biofuel feedstock. In Malaysia, about 10% of the palm oil plantation is currently on peat land (that accounts for 4.2 million hectares of land) (Chiew 2007). As peat land is considered to be a globally important stock of soil carbon and acts as a net sink of atmospheric carbon dioxide, its utilization as an agricultural land area would increase the carbon dioxide flux into the atmosphere and hence contribute to global warming (Waddington, Strack and Greenwood 2010, Hirano et al. 2009). Clearing vegetation cover and replacing natural habitats with cropland by burning (to clear forestland) and tilling, releases CO_2 trapped in the plant biomass and in the soil. The amount of CO_2 released during the first fifty years of changing the land use is called the “carbon debt” of land conversion (Fargione et al. 2008). As energy crops can sequester CO_2, this carbon debt can be ‘repaid’ over time. It is suggested that the temporal boundary in lifecycle assessments be based on the payback period of the carbon debt. Fargione et al. (2008) mentioned, “Until the carbon debt is repaid, biofuels from converted lands have greater GHG impacts than those of the fossil fuels they displace.” Besides the carbon debt, the role of soil carbon in the overall sustainability of biofuels must be understood in order to study LUC and assess its long-term impacts. Carbon sequestration by the plant

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[43] Soil degradation may occur due to erosion by water and wind, salinization, loss of nutrients, soil organic matter depletion.

biomass is at the core of the idea of GHG savings. Carbon sequestration goes hand in hand with soil carbon, which in turn is integrally linked with soil quality (and therefore, crop yield). Soil carbon plays a significant role in the water- and nutrient-holding capacity, the resistance to erosion and the overall structure of the soil. Besides, soil carbon also provides energy to the soil microorganisms (Lal 2004). Lal (2004) has referred to soil carbon as "soil's life support system". Soil carbon content can be improved by using recommended manufacturing practices, the application of organic matter as nutrients (e.g., byproducts – seed cake and husks in case of jatropha) and fertilizers[44].

However, one must bear in mind that the soil carbon content in highly degraded lands could be lower than the optimum value required for sustainable agricultural practices. Jatropha cultivation on such lands will result in low yields. The soil carbon incorporated into the plant biomass will not be replenished as the byproducts yield is too low and the fertilizer demand would be too high. Moreover, as mentioned before, the use of large amounts of fertilizers will diminish the GHG savings promised by biofuels. Continued cultivation in such low-yield areas will deplete soil carbon, result in progressively lower yields, thereby resulting in an unsustainable practice. For degraded areas which do have optimum levels of soil carbon, it is possible to improve the soil carbon content by adhering to recommended manufacturing practices (RMPs). As Lal (2004) has mentioned, sustainable agricultural practices will help break the

[44] Lehmann (2007) has suggested the use of biochar for as an innovative method for increasing soil carbon. Biochar is obtained by the low temperature pyrolysis of plant biomass (grasses, crop residues etc.). Lehmann has mentioned that biochar has "twofold higher carbon content" than plant biomass and has suggested that putting biochar back in the soil would help in trapping carbon in the soil.

"vicious cycle of declining productivity–depleting soil organic carbon stock–lower yields".

The lack of reliable data for yield and land use change raises questions about jatropha's sustainability. Trabucco et al. (2008) mentioned that if jatropha plantations in 'marginal' areas were considered only, then the projected reduction (by 2015) in global oil consumption would be only 3%. If yields in marginal areas prove to be too low, other fertile areas might need to be devoted for jatropha cultivation. This would raise concerns about deforestation and the possible competition with food crops. This would also be in direct conflict with the frequently mentioned advantage of jatropha – that its cultivation involves a high energy-output-to-input ratio and it is not very 'resource hungry' as a biofuel feedstock. For a positive energy balance of jatropha, the use of fossil fuels (in the machinery used in various stages of biofuel production) and chemical fertilizers should be minimized, as these result in significant energy consumption (Ovando-Medina et al. 2009). Keeping the concerns about jatropha's sustainability in mind, it is vital to reevaluate jatropha's lifecycle performance.

There are always uncertainties in LCA studies. Rebitzer et al. (2004) mentioned that LCA is "still a young and evolving application" and that there are "different approaches, depending on the specific question at hand, and ultimately depending on the decision that has to be supported by an LCA study". However, until a more robust methodology is developed, LCA will be an uneven 'baseline' for comparative studies of sustainability of alternative fuels.

Toxins and anti-nutritional factors in jatropha:

Jatropha curcas has been proposed as a promising source of non-edible vegetable oil for biodiesel production. As mentioned before, jatropha can grow on arid soils, improve the soil structure and help in land reclamation. Jatropha also has several medicinal and antimicrobial properties. Makkar et al. (1997) studied the nutritive potential of eighteen varieties of *Jatropha curcas* and found the crude protein concentrations of the jatropha seedcake to range from 19 - 31 percent (on a dry matter (DM) basis). In their experiments on the recovery of protein from jatropha seedcake, Makkar et al. (2008) obtained 330 g kg^{-1} and 295 g kg^{-1} of protein from the residual oil-containing seedcake and the defatted seedcake, respectively. However, the presence of several toxins in the seeds makes the seedcake unsuitable as an animal feed. Rakshit et al. (2008) conducted toxicity studies on rats, using treated and untreated jatropha meal. Their studies showed reduced appetite and low diet intake, diarrhoea, reduced motor activity and significant changes in body weight of the rats. The rats fed with treated[45] meals showed delayed mortality compared to those fed with untreated meals. The authors also found that higher the residual oil content in seed cake, higher the phorbol esters concentration and thus, higher the toxicity of the seedcake. Ahmed and Adam (1979) studied the toxicity of jatorpha on sheep and goats. They reported that jatropha poisoning caused haemorrhage in the rumen,

[45] Jatropha meal was treated with aqueous solution of either 2% NaOH or 2% $Ca(OH)_2$ and then autoclaved at 121 °C for 30 min. The samples were dispersed in water in a ratio 1:5 (w/v) and kept for one hour. The excess alkali and soluble tannins were removed by filtering through muslin cloth. The residue was dried at 90 ± 5 °C (Rakshit et al., 2008).

reticulum, lungs, kidneys and heart of the animals. At present, the seedcake is primarily used as natural fertilizer. Detoxification of the seedcake will significantly enhance its value as a byproduct.

Among the several anti-nutritional factors present in jatropha, phorbol esters have been identified as the primary toxins (e.g., Makkar and Becker 1998, Aregheore, Becker and Makkar 2003). Phorbol esters are naturally occurring diterpenes found in the Euphorbiaceae and Thymeliaceae plant families (Haas and Mittelbach 2000, Dimitrijevic et al. 1996). Besides jatropha, several plants such as *Sapium indicum, S. japonicum, Euphorbia frankiana, E. cocrulescence, E. ticulli, Croton spareiflorus, C. tigilium, C.ciliatoglandulifer, Excoecaria agallocha, and Homalanthus nutans* are reported to contain toxic moieties of phorbols. Haas et al. (2002) isolated six unstable intramolecular diterpene esters from the seed oil of *Jatropha curcas.*

Phorbol esters exert several biological effects such as cell proliferation, tumour promotion, inflammation and lymphocyte mitogenesis (Aitken 1986). The biological effects of phorbol esters depend on the structure of the compound. (The alcohol moiety called phorbol is inactive and non-toxic.) Phorbol esters by themselves do not induce tumours but promote tumour growth following exposure to a carcinogen at a subcarcinogenic dose. Therefore, they are classified as cocarcinogens and tumour promoters (Goel et al. 2007). The mechanism of phorbol esters' toxicity is related to the protein kinase C (PKC), the major receptor of phorbol esters (e.g., Wink et al. 2000, Hundsdoerfer et al.

2005, Makkar et al. 1997, Goel et al. 2007). PKC is a family of kinases which controls intracellular signal transduction and gene expression (Dimitrijevic et al. 1996). The activation of PKC results in a variety of cellular responses. The interaction of phorbol ester with PKC affects the activities of several enzymes, biosynthesis of protein, DNA, polyamines, cell differentiation processes, and gene expression.

Degradation of phorbol esters in jatropha oil during biofuel production:

In their studies of the degradation of phorbol esters in the different steps of biofuel production, Makkar et al. (2009) and Haas and Mittelbach (2000) measured the phorbol esters content in different fractions of jatropha oil obtained at various stages of processing (degumming, neutralization by acid, bleaching, silica treatment and deodorization (or stripping)). Makkar et al. (2009) found that the phorbol esters' content differed for solvent extraction and cold pressing. While Makkar et al. (2009) found that degumming resulted in a 20% reduction in phorbol ester content in the case of solvent extracted oil and 4% in case of cold pressed oil, Hass and Mittelbach (2000) reported that degumming did not result in any appreciable decrease in the concentration of phorbol esters concentration. Although silica treatment reduced phorbol esters by 8% for solvent extraction, no appreciable decrease in phorbol esters concentration was seen for cold pressed oil (Makkar et al. 2009). (Hass and Mittelbach (2000) did not carry out silica treatment). Hass and Mittelbach (2000) reported that neutralization of acid followed by bleaching reduced phorbol esters content by 45%. Makkar et al.

(2009) found that deodorization[46] reduced the phorbol ester content to non-detectable levels. However, Hass and Mittelbach (2000) mentioned that deodorization[47] was ineffective in reducing the concentration of phorbol esters. The variation in the results of deodorization may be explained by the difference in the deodorization conditions used in the two studies. Makkar et al. (2009) noted that the nature and toxicity of the degradation byproducts are currently unknown.

Detoxification of phorbol esters:

Phorbol esters' concentration in jatropha seedcake can be decreased by different chemical treatment methods (e.g., Haas and Mittelbach 2000, Aregheore et al. 2003). Phorbol esters are heat stable and could not be destroyed by heat treatment for 30 minutes at 160 °C. (Makkar and Becker 1998). Aregheore et al. (2003) treated defatted jatropha meal with sodium hydroxide in combination with sodium hypochlorite and distilled water, followed by heat treatment at 121 °C for 30 minutes. Increasing the sodium hydroxide concentration from 2 - 3.5% (w/w, without using sodium hypochlorite) decreased the phorbol esters concentration from 0.89 - 0.18 mg g^{-1}. Using 10% (v/w) sodium hypochlorite and increasing the sodium hydroxide concentration from 2.5 - 4% (w/w) decreased the phorbol esters concentration from 0.22 - 0.13 mg g^{-1}. Using 2% (w/w) sodium hydroxide

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[46] The deodorization of the raw jatropha oil was done in a laboratory-scale deodorizer at 260 °C and 3 millibar with 1% steam injection for one hour (Makkar et al., 2009).

[47] The raw jatropha oil was steam distilled at 200°C at "normal" pressure for two hours (Haas and Mittelbach, 2000). The authors did not mention the exact pressure or the composition of the steam used for stripping.

and increasing the sodium hypochlorite concentration from 15 - 25% (v/w) decreased the phorbol esters concentration from 0.46 - 0.24 mg g^{-1} Heat treatment followed by washing four times with 92% methanol reduced the phorbol ester content from 1.78 mg g^{-1} to 0.09 mg g^{-1}. As mentioned before, conventional steps in oil refining can significantly reduce the phorbol ester content in jatropha seed oil. Although degumming and deodorization steps did not show any effect, neutralization and bleaching reduced the phorbol ester concentration by almost 50%. The mechanism suggested for this is the hydrolysis of phorbol esters resulting in partial detoxification (Haas and Mittelbach 2000).

Other anti-nutritional components:

Besides phorbol esters, several other toxins and anti-nutritional factors are found in jatropha seeds.

Trypsin inhibitors:

Trypsin inhibitors reduce the digestibility of the proteins by directly interacting with the proteolytic enzymes secreted by the pancreas (Hajos et al. 1995). Trypsin inhibitors are almost completely inactivated by heat treatment. van der Poel et al. (1990) described the temperature effects on trypsin inhibitors by first order kinetics, in which the inactivation occurred in two stages with differing reaction rates. Trypsin inhibitors obtained from winged bean meal were stable upon heat treatment at 60 °C for 60 minutes. Incubation at 80 °C for 5 minutes resulted in complete inactivation. Microwave treatment on the extract had no effect on the trypsin inhibitors in the meal. Infrared treatment of the meal for 60 seconds inactivated most of the trypsin inhibitors (Kadam and Smithard 1987). Heat treatment at 160 °C resulted in rapid inactivation of trypsin inhibitors in jatropha meal (Aderibigbe et al. 1997).

Lectins:

Lectins are carbohydrate-binding proteins that bind reversibly to specific monosaccharides or oligosaccharides (Van Damme et al. 1998, Van Damme, Lannoo and Peumans 2008, Arora et al. 2005, Reddy and Pierson 1994). Lectins play an important role in the plant's defense against pests. As with trypsin inhibitors, lectin activity decreases with heat treatment (Aderibigbe et al. 1997). Extraction with ethanol, followed by treatment with sodium bicarbonate considerably decreased lectin activity (Martinez-Herrera et al. 2006).

Phytate:

Phytate levels in jatropha meal reduce the bioavailability of minerals, especially Ca^{2+} and Fe^{2+} (Martinez-Herrera et al. 2006). Phytates can also form complexes with enzymes such as trypsin and pepsin and reduce protein digestibility (Reddy and Pierson 1994). Phytates are not heat labile and are resistant to heat treatment (Makkar, Aderibigbe and Becker 1998). Heat treatment with 80% moisture at 160 °C for 30 minutes did not decrease the phytate content appreciably (Aderibigbe et al. 1997). Treatment of defatted jatropha meal with sodium bicarbonate, followed by irradiation at 10 kGy[48] (at dose rate of 19.70534[49] Gy per minute) resulted in a slight reduction in the phytate content (Martinez-Herrera et al. 2006).

Saponins:

Plant saponins are known to have antimicrobial properties. Saponins protect the plant from insects and pest and inhibit mould (Francis et al. 2002). The bittersweet taste of saponins can make jatropha seed meal unpalatable for animals. Saponins are also known to have beneficial effects, such as reduction of plasma cholesterol in several mammalian species (Milgate and Roberts 1995, Reddy and Pierson 1994). Saponin content in jatropha meal was reduced by 50% by extraction with ethanol followed by treatment with sodium bicarbonate. However, the reduction was attributed mainly to the extraction step (Martinez-Herrera et al. 2006). The concentration of saponins is reported to be reduced by fermentation but not by cooking, indicating that heat treatment may be ineffective for the reduction of saponin concentration (Reddy and Pierson 1994, Aderibigbe et al. 1997).

Phenols:

Plant phenols are secondary metabolites that provide protection from animals feeding on them (Singleton 1981). Phenolic compounds (such as flavonoids,

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[48] gray (Gy): SI unit of radiation dose.
Radiation dose is the amount of energy deposited per unit of mass. One gray (Gy) is defined to be the dose of one joule of energy absorbed per kilogram of matter (named after the British physician L. Harold Gray) [7, 143]

[49] The number is presented as mentioned in the original paper by Martinez-Herrera (2006).

phenolic acids, stilbenes, tannins and lignin) are important for plant metabolic processes and the normal growth and development of plants and are essential for the defense against infection and injury (Kahkonen et al. 1999). Phenols also have antioxidant properties. It is interesting to note that the antioxidant properties of phenolic compounds in jatropha may be useful in slowing the degradation of jatropha oil and biodiesel (El Diwani et al., 2009). In the detoxification experiments using jatropha seedcake, negligible amounts of total phenols were found after heat treatment (Aderibigbe et al. 1997, Makkar et al. 1998, Martinez-Herrera et al. 2006).

Several other toxins such as amylase inhibitors and cyanogenic glucosides are found in jatropha seeds. Aderibigbe et al. (1997) mentioned that these toxins were not detected after heat treatment of the seed meal.

At present, chemical methods of detoxification of jatropha seedcake are feasible only on a laboratory scale only. These methods are not economically viable for large-scale application. Also, using chemicals and solvents for detoxification on a large scale raises environmental concerns about their disposal. Besides heat- and chemical-treatment procedures, ozonation can potentially provide another means of detoxification of jatropha seedcake. Ozonation of jatropha seed extract showed significant reduction in the concentration of phorbol esters. (The methods and the results of the ozonation experiments are presented in the Appendix.) As mentioned earlier in the chapter on lifecycle assessment, the end use of the byproducts can significantly improve the lifecycle 'behaviour' of jatropha's agriculture. Therefore, advancements in detoxification of the nutrient-rich jatropha seedcake are essential to improve its value as a byproduct.

The water footprint of jatropha:

Biofuels can potentially help in reducing the emission of greenhouse gases (GHGs). At the same time, there are growing concerns about the shortage of water in many parts of the world[50]. Therefore the expected water usage must be rigorously calculated before allocating the any part of the available water resources for biofuel production. As the land and water are integral to agro-based products such as biofuels, a thorough evaluation of the water footprint of biofuels is essential to formulate sustainable biofuel programmes. Advocates of jatropha cultivation have proposed that the plant will not compete with food crops, as it can be grown in degraded and marginal lands. However, jatropha yields per hectare would have to be high[51] for jatropha-based biodiesel to compete with and significantly decrease fossil fuel consumption. Without any additional inputs (e.g., fertilizers and irrigation) jatropha yields from degraded lands might not be sufficient to meet the increasing demands for biodiesel.

While jatropha seedcake and animal waste may be applied as natural fertilizers to partially offset the requirement for chemical fertilizers and other agrochemicals, irrigation requirements may prove to be the major bottleneck in increasing yields in marginal lands. Irrigation requirements can be partly offset by

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50 The WHO has reported that about 1.2 billion people live in areas where the water is physically scarce (www.who.int). According to the Food and Agriculture Organization (FAO): "By 2025, 1800 million people will be living in countries or regions with absolute water scarcity, and two-thirds of the world population could be under stress conditions." (www.fao.org)

51 As there is considerable variability in the reported values of jatropha yields from field studies, the terms 'high' and 'low' are used only qualitatively to refer to yield.

using treated wastewater[52] from the settlements close to jatropha plantations. Due to the limitations of mechanized agricultural technologies, jatropha cultivation and harvesting in developing nations will be done manually, in most cases. Therefore, sections of the population may need to relocate close to the plantation sites. A sudden relocation of a population to a new site will affect the consumption and recycling patterns of the surrounding water resources. Improper waste management and agricultural runoff containing fertilizers and pesticides may also pollute the the water bodies in the nearby areas. In such cases, wastewater treatment facilities can serve the dual purpose mitigating pollution and providing water for irrigation. However, the treated effluent must adhere to the agricultural water quality standards[53]. Only then can the wastewater be used for irrigation, and help in reducing the jatropha's water footprint.

Gerbens-Leenes et al. (2009) calculated the water footprint for several crops including jatropha. According to the authors, jatropha is the least efficient bioenergy[54] feedstock in terms of water usage. The authors report the total[55]

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[52] In its report *"Crops and Drops: Making the best use of water for agriculture"*, the FAO provides the following estimate: "As an example, a city with a population of 500000 and a water consumption of 120 litres.day^{-1} person^{-1} produces about 48000 m^{3}.day^{-1} of wastewater (assuming 80 percent of the water used reaches the public sewerage system). If this treated wastewater were used in carefully- controlled irrigation at a rate of 5000 m^{3}/ha/year [m^{3} ha^{-1} year^{-1}], it could irrigate some 3500 hectares."

[53] According to the World Health Organization (WHO): "More than 10% of people worldwide consume foods irrigated by wastewater that can contain chemicals or disease-causing organisms." [16]

[54] Gerbens-Leenes et al. (2009) have assumed that the total biomass produced was utilized in the generation of bioenergy. The water usage estimates are expressed as m^3 of water required per GJ of energy

water footprint for jatropha to be 396 m^3GJ^{-1}, while those for soybean and sugarcane were 173 m^3GJ^{-1} and 50 m^3GJ^{-1} respectively. Thus, they conclude that jatropha has a significantly higher water footprint as a biodiesel feedstock, as compared to other energy crops.

By relating the bioenergy yield with the water usage, the authors provided a baseline for comparing the water footprints of different plants. However, the results do not depict the actual water footprint of jatropha. Jatropha will be grown primarily for biodiesel production. Therefore, more accurate units for water usage would be m^3 of water per GJ of energy from biodiesel (instead of heat and electricity). If byproducts are taken into account, then calculations must also include the energy content of the seedcake and the husks. Secondly, the authors assumed that the total plant biomass will be used for energy production. Again, this is not true for biodiesel production[56].

(electricity) produced (units: m^3GJ^{-1}). The bioenergy in the calculations included heat, electricity, bioethanol, and biodiesel.

[55] In this study, Gerbens-Leenes et al. (2009) have divided the water footprint was divided into two categories: blue water and green water.
Blue water: runoff water used for irrigation (including surface water and groundwater.)
Green water: Water that is available on-site (soil moisture and rainfall).
'Total' water footprint refers to the sum of blue and green water.

[56] Plant byproducts (e.g., husks and stalks) may still be used as boiler feed in cogeneration plants to produce electricity and reduce the consumption of fossil fuels during biodiesel production.

Maes et al. (2009a) describe the calculations by Gerbens-Leenes et al. (2009) as "dramatically overestimated" as the effect of evapotranspiration[57] has been ignored in their calculations. Maes et al. (2009a) also mentioned the results of another study by Kheira and Atta (2009) to argue that the water usage calculations by Gerbens-Leenes et al. (2009) are incorrect. In their studies, Kheira and Atta (2009) made rigorous calculations to determine the water use efficiency of jatropha, while taking evapotranspiration effects into account. They reported the average water consumption rate of jatropha to be 6 L $week^{-1}$ throughout the growing season (75 days) and concluded that "jatropha can survive and produce full yield with high quality seeds under minimum water requirements, compared to other crops"[58].

Although the study by Kheira and Atta (2009) involves rigorous calculations of water usage, the results of the study are site-specific. Therefore, the claims of Gerbens-Leenes et al. (2009) cannot be disputed merely by comparing their results with the field data from another site. Knowing that jatropha yields are dependent on environmental conditions, it is not advisable to draw sweeping

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57 Over 90% of the water required by terrestrial plants is not 'used' in any biochemical way but lost through transpiration (Morison et al., 2008). All water usage estimates must take into account the losses by transpiration and soil moisture evaporation. As evapotranspiration depends on several other variables (such as solar radiation, temperature, vapour pressure, relative humidity and wind speed) accounting for evapotranspiration would incorporate these variables into the calculation.

58 In this study, the authors have not compared jatropha's water usage efficiency. The authors have used farmyard manure and "recommended" dosage of NPK fertilizer. Neither the exact fertilizer dose is mentioned, nor is the term "recommended" explained. As young plants were used in this study, there are uncertainties regarding the water usage in case of full-grown, mature plants.

conclusions about the water footprint of jatropha based on the studies in a single area.

Gerbens-Leenes et al. (2009) mentioned that as per their assumptions, the water use estimations are conservative. The authors assumed that the water use by the crop is equal to the crop's actual water requirement. In arid conditions, the actual water consumption will be lower than the calculated values when water stress occurs. The authors also mentioned that the future agricultural yields may improve and therefore, their assumed values for yields would be lower than the actual future yield values. Hence, the predicted water footprint would be larger than the actual value. In their report on the GHG performance of jatropha, Dehue and Hettinga (2008) reported that jatropha does not yields seeds until the fourth year; yield increases till the ninth year and thereafter remains steady till the twenty-third year[59]. Thus, the water footprint based on the field studies on younger plants is likely to be overestimated.

Gerbens-Leenes et al. (2009) also made "optimistic assumptions" about the conversion efficiencies of different biomass to bioenergy:

> "For the efficiency of obtaining electricity or biofuels from biomass, we have made optimistic assumptions by taking theoretical maximum values

59 Dehue and Hettinga (2008) have reported the yields in the different years as follows (the numbers presented are from the original document):

Year	1-3	4	5	6	7	8	9-23
Seed yield (t/ha)	0	2.5	3.75	5	5.625	6.25	6.875

or values that refer to the best available technology. These assumptions mean that the resulting WF [water footprint] figures are conservative."

The authors' explanation of how this assumption affects the calculated water footprint seems incorrect. If the assumed conversion efficiency were higher, the calculated water footprint (m^3GJ^{-1}) would be lower as less water would be required to produce one unit of bioenergy. To an extent, this would compensate for the conservative estimations discussed earlier. It is therefore recommended that all assumptions and their effects should be carefully evaluated (and quantified, where possible) and factored into the calculated results.

Jongschaap et al. (2009) also pointed out that the data used by Gerbens-Leenes et al. (2009) is inconsistent as yield data from non-irrigated young plantations have been combined with water use data of mature plantations. Maes et al. (2009a) mentioned that during the initial years of cultivation, there would be little growth in the reproductive biomass (flowers and fruits). Primarily, the non-reproductive biomass would grow during the first three years of plantation. Hence, the water footprint calculated by Gerbens et al. (2009) is unrealistically high.

In another study of the plant-water relationships for jatropha and the response of jatropha seedlings to water stress, Maes et al. (2009b) classified jatropha as a stem succulent plant with low stem density (0.26 g^{-3}) and high stem-water content. Stem-succulent species rely on their stem-water reserves during drought conditions and cannot access water in the deeper layers. The authors theorized that for stem succulent plants, the plant-water relationship is likely to remain independent of the plant's age[60]. If this is true, then, all conditions remaining constant, the water usage estimates based on the younger plants might be representative of the actual water footprint of mature plants, within acceptable margins of error. Further studies on the water usage of mature jatropha plants are recommended to verify the validity of this theory.

In the context of jatropha's water usage, another area that merits attention is the use of proper and consistent units for expressing the water footprint. Besides rainfall and irrigation, seed yield will depend on several factors such as plant age, soil characteristics, agricultural practices and the use of fertilizers and agrochemicals. Biodiesel yield in turn will depend on seed yield, oil extraction procedure, and the efficiency of transesterification process. All of these factors must be incorporated into the calculations and units used to express the water usage. Therefore, units other than biomass yield[61] per unit of water or energy yield per unit of water may be required to express water footprint. In the following section, water use efficiency (WUE) is discussed as another means of quantifying water usage.

Xu and Hsiao (2004) defined WUE at the physiological level as the ratio of photosynthesis to transpiration. Citing that CO_2 fluxes across the leaf are highly

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[60] The authors have recommended further studies on the plant-water relationships of mature jatropha plants (Maes et al. 2009b).

[61] While expressing water usage in terms of biomass yield, it must be clarified whether the calculations use plant total biomass or the aboveground biomass only.

variable[62], the authors noted that photosynthetic WUE is difficult to monitor for long periods of time and suggested the use of biomass-based WUE instead. Morison et al. (2008) also pointed out that based on the scale of reference, WUE may be calculated in terms of the economic[63] yield or the biomass yield.

Jongschaap et al. (2007) presented a calculation for water usage based on WUE. The authors calculated the molecular weight of jatropha oil from the following chemical structure of jatropha oil:

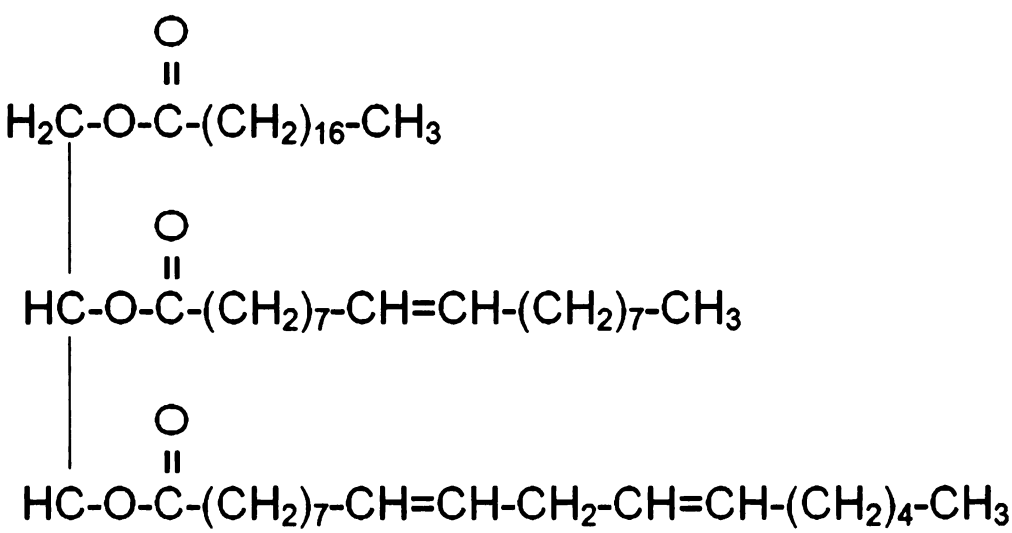

Figure 1 - Chemical Structure of jatropha oil

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62 Jie et al. (2008) have shown the variability of WUE in six tree species (*Prunus. avium*, *P. pseudocerasus*, *P. armeniaca*, *P. persica*, *P. salisina* and *Malus pumila* Mill). In their studies, WUE was the highest at 7:00-8:00 am, the lowest at noon, increased 16:00-17:00 pm. Moreover, WUE was higher in autumn than that in summer at the same time of the day. This diurnal and seasonal variability suggests that it could be more beneficial to measure the biomass WUE. However, photosynthetic WUE is important for a better understanding of the physiological response of jatropha to water stress.

63 By economic yield, the authors could either be referring to the financial gain per unit of water used or the economically viable, end product yield (e.g., biodiesel in case of jatropha) per unit of water consumed.

Each molecule of jatropha oil comprises of 57 C (12 g mol^{-1}), 107 H (1 g mol^{-1}) and 6 O (16 g mol^{-1}). Hence, the molecular weight of jatropha is calculated to be about 0.888 $gmmol^{-1}$ [64].

The basic photosynthesis reaction is:

$12\ H_2O + 6\ CO_2 + light \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$.

It is assumed that the jatropha plant obtains all carbon required for the formation of oil from photosynthesis. Therefore, 57 mmol CO_2 are required for 57 mmol of carbon in jatropha oil.

The photosynthetic WUE values of *Jatropha pandurifolia* L. and *Jatropha gossypifolia* L. were reported as 3.68 mmol CO_2 (mmol $H_2O)^{-1}$ and 2.52 mmol CO_2 (mmol $H_2O)^{-1}$ respectively[65]

Jongschaap et al. (2002) assumed a WUE value of 3 mmol CO_2 (mmol $H_2O)^{-1}$ for *Jatropha curcas* L. This means that the assimilation of 3 moles of CO_2 would require 1 mole of H_2O. Similarly, 57 mmol of CO_2 correspond to 19 mmol H_2O (or 0.342 g H_2O). Therefore, 0.342 g H_2O is needed to produce 0.888 g of oil.

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[64] All numbers are presented as in the original paper.

[65] Jongschaap et al. (2007) have noted that the WUE values reported by Li Guo (2002) are close to those of other oil seed species such as soybean (3.90 mmol CO_2 (mmol $H_2O)^{-1}$ and oil palm (3.95-4.42 mmol CO_2 (mmol $H_2O)^{-1}$.

Assuming the density of water and jatropha oil to be 1 kg L^{-1} and 0.92 kg L^{-1}, the water consumption was calculated to be 0.345 L water (L oil)$^{-1}$.

The authors mention that in this calculation, plant processes other than transpiration were ignored. Although such simplifications can help in making rough estimates and 'back-of-the-envelope' calculations, these simplistic calculations will not yield accurate estimations of water usage.

Besides accounting for the effects of evapotranspiration and CO_2 fluxes, WUE may also provide a means to predict the water usage in one site, knowing the WUE values at another site with different environmental conditions. The variability of WUE with environmental conditions and CO_2 levels in the atmosphere may therefore be an added benefit in expressing water usage. While it may not be feasible to have one constant WUE value for jatropha, knowing the WUE values of the plant at one site could help in estimating the WUE value in another region using empirical equations[66] and models. Such models would help in integrating the results of water usage estimates in different regions.
In his "opinionated review", Blum (2009) argued that effective use of water (EUW), not WUE, is the key to obtaining better yields in water stressed

[66] Hsiao (1993) had proposed empirical equations to WUE values in a new set of conditions from the original WUE values and reference conditions. Upon testing these equations to predict WUE values of cotton and maize, under irrigated conditions, Xu and Hsiao (2004) found the equations to work "surprisingly well". However, the validity of such equations should be tested in water-stressed conditions as well. More research on formulating empirical equations and model to predict WUE values is recommended.

conditions[67]. The argument presented by Blum is sound. While WUE is a measure of a plant's performance in different conditions, it is not the answer to improving yields. However, WUE is still suggested as a possible 'unifying' unit to quantify water usage to improve the 'generalizability' of the data generated in different field studies.

The results of water usage may also be made more 'transferable' by using weights and indices in the calculations of water usage. This would also help in reducing the margins of uncertainty in the calculations for water usage. Indices may be defined on the basis of rainfall conditions, existing facilities for irrigation, proximity of natural water bodies, possibility of using effluent from wastewater treatment facilities, pumping costs, elevation[68], possibility of rainfall harvesting and other factors that contribute to the water footprint of jatropha. These weights and indices, when factored into the calculations for water usage, would help in using the field data from one site and estimating the water usage in another region with different conditions[69].

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67 Blum explains EUW as follows: "Effective use of water (EUW) implies maximal soil moisture capture for transpiration which also involves reduced non-stomatal transpiration and minimal water loss by soil evaporation." Blum has also mentioned genetically increased drought resistance capacity of plants through improved biochemistry of photosynthesis combined with other biotechnological advancements is the key to obtaining higher yields in water stressed conditions.

68 Elevation can play a significant role in high altitude areas with adequate rainfall especially in developing nations, where the runoff water can be harvested and used for irrigation without requiring elaborate pumping facilities.

69 In their studies, Pfister and Hellweg (2009) have used a water stress index (WSI) to account for the scarcity of water in the area under consideration.

Studies incorporating weights and indices in the actual field data must clearly present all the assumptions built into the calculations along with the basis on which the values of weights are decided. Also, the difference in soil characteristics and agricultural techniques should be accounted for in the assessment of water usage. The importance of clearly representing the generated data from field studies is underscored by the fact that future policies on land and water usage to support biofuel programmes will be formulated on the basis of these studies.

As discussed before, biotechnological advancements[70] hold the key to improved drought tolerance, higher yields and overall sustainability of jatropha. Another strategy to improve drought tolerance of jatropha is the use of symbiotic microorganisms. The Energy and Resources Institute (TERI), India) has successfully used mycorrhizal associations[71] to obtain improved yield[72] from jatropha seedlings. Mycorrhizae have been shown to increase the drought

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[70] The African Agricultural Technology Foundation (AATF) has joined the International Maize and Wheat Improvement Center (CIMMYT) and Monsanto (a private agricultural company) in a public-private partnership called Water Efficient Maize for Africa (WEMA) to develop a drought tolerant, high yielding variety of maize, suitable for African conditions. Similar research is recommended to develop biotechnologically advanced varieties of jatropha for higher yields and improved water usage.

[71] Mycorrhizal fungi have coevolved with plants and soils for over 400 million years. They form symbiotic associations with plants and coexist by forming colonies in the roots and trading inorganic nutrients and water with the plants for carbon (sugars). This is especially important in degraded soils where nutrients, which might have otherwise been unavailable to plants, can be accessed via the mycorrhizal fungi. Thus, in such symbiotic interactions, plants show enhanced tolerance to environmental stresses. In case of jatropha, the mycorrhizal interactions are interesting in light of the antimicrobial properties of the plant. [27]

[72] The 'mycorrhized' seedlings showed 95% success in seed germination, as compared to 50% success with non-mycorrhized seeds. Yields improved by 20%-30% after mycorrhizal inoculation (TERI, India).

resistance of loblolly pine (*Pinus taeda* L.) and rose (*Rosa hybrida* L. cv. Ferdy) (Davies et al. 1996). Soybean seed weight was shown to improve by the use of arbuscular mycorrhizal fungi (Aliasgharzad, Neyshabouri and Salimi 2006). An 8.0% increase in yield was seen after inoculating wheat (*Triticum aestivum* L.) seeds with *Azospirillum brasilense*, a plant growth-promoting rhizobacterium (PGPR) (Diaz-Zorita and Fernandez-Canigia 2009). Besides enhancing the drought tolerance in plants, symbiotic microorganisms also improve the soil characteristics such as porosity, saturated hydraulic conductivity (Celik, Ortas and Kilic 2004) and soil moisture retention (Auge et al. 2001). By making soil nutrients more accessible to plants, these organisms reduce the dependence on agrochemicals. Mycorrhizal fungi can sequester CO_2 [27] from the air with the help of their fungal filaments and enrich soil carbon. Thus, symbiotic microorganisms such as mycorrhizal fungi can help in improving soil quality in degraded lands, thereby increasing yield and ultimately reducing the water footprint of jatropha. Further research on other genetically improved symbiotic microorganisms is recommended.

Once the water consumption for jatropha cultivation is estimated, the next step is to formulate policies for agricultural water management vis-à-vis biofuels. Sound water management policies and sustainable irrigation practices are essential for the successful implementation of biofuel programmes. Some of the major issues and challenges in water management are discussed in the following section.

Challenges in water management:

Developing nations with growing economies (e.g., China and India) are actively pursuing biodiesel programmes involving jatropha. Insecurities of food shortage, the promise of rural development from jatropha cultivation, favourable climatic conditions, reduction of imported oil and additional revenue from sustainable practices[73] are some of the reasons why these nations favour biodiesel from jatropha over ethanol from corn or sugarcane. While domestic biofuel is attractive from the point of energy security, there are several concerns about the sustainability of biofuel programmes which must be addressed.

Countries such as India and China rely heavily on irrigated agriculture (de Fraiture, Giordano and Liao 2008). Therefore, it is important to evaluate the additional stess that jatropha cultivation would put on the limited freshwater supplies in these regions. The concerns about unsustainable irrigation practices are even more pertinent in countries like Africa where water is a precious and often rare commodity. A major concern with biofuels is the irrigation requirement for feedstock cultivation, which is the most water consuming step[74] in biofuel production. However, the water consumption in the actual production process

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[73] e.g., via Clean Development Mechanism (CDM) credits (Larson, 2008).

[74] Corn cultivation in Nebraska requires intensive irrigation. The irrigation requirements show that the production of each gallon of ethanol requires 1568 gallons of water (Varghese, 2007). From the water use efficiency data from Minnesota's ethanol plants, the average water consumption for each gallon of ethanol was 5.9 gallons of water in 1998 and 4.5 gallons of water in 2005 (The numbers are calculated from the data from Keeney and Muller, 2006).

(i.e., in the processing plants) will have local effects[75] on the areas close to the biofuel production plants. Therefore, while evaluating the water footprint of biofuels, these local 'water stresses' should be taken into account, in addition to the larger irrigation requirements.

With the increasing awareness of water-related sustainability issues, nations all over the world are undertaking projects and formulating policies to improve their water security. Recent examples of ambitious water management projects include the South-to-North Water Diversion (SNWD) project in China[76], the Inter-Basin Water Transfer project (IBWT, or the 'Interlinking of Rivers') in India[77] and

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[75] For example, Coca Cola has been accused of exploiting the water resources in the small village of Plachimada (Kerela, India). The operation of Coca Cola's beverage factory is said to have caused groundwater depletion due to unsustainable exploitation of the groundwater. The company also supplied the industrial waste sludge for use as fertilizer to the local farmers. Upon testing the samples at the University of Exeter (UK), it was found that the sludge contained a number of toxic chemicals including cadmium and lead (BBC, (2003), Aiyer, (2007)) The application of the sludge as a fertilizer also resulted in the contamination of the local water supply.
Biofuel production plants in developing nations raise similar concerns, especially because the environmental laws and regulations in developing nations are neither as powerful nor as strictly implemented as in the industrialized nations.

[76] Mao Zedong proposed the idea of the diversion project in 1952. The SNWD project aims at drawing water from the rivers in southern China and supplying to the drier regions in northern China. The main rivers involved in this water diversion project are the Yangtze, Yellow River, Huaihe and Haihe rivers. Displacement of large portions of the population, proposed industrialization along the diversion path and the resulting pollution, loss of natural habitats – these are some of the major concerns surrounding this project [14]. Similar concerns were expressed when the Three Gorges Dam project was proposed. The dam was supposed to control the flow of the Yangtze River during floods. During the floods in 1998, four thousand people died and fourteen million people became homeless. The economic losses were estimated to be twenty four billion dollars. [13]

[77] The government of India has proposed to join thirty-seven rivers through thirty links (fourteen in northern India and sixteen in peninsular India), to address the spatial mismatch between the availability and the demand of water in different parts of India. The project is deemed controversial and there are serious concerns about the feasibility and long-term environmental, socio-economic and political impacts of such a large-scale project. *'River Linking: A Millenium Folly?* is a compilation of articles on socio-economic and technical issues surrounding this project. (Medha Patkar, a renowned social rights activist is the editor of this book. She is actively involved in the issues related the riparian rights vis-à-vis river water diversion projects.) An online booklet by Rivers for Life (an independent research action group) is recommended for

the proposal to divert the Hailaer River to Dalai Lake on the Russia-China border[78]. In the United States, several projects for diverting water from the Great Lakes[79] have already been implemented.

While such projects which aim at sustainable water management and efficient irrigation practices are being proposed and implemented, it is essential to evaluate the long term consequences of these projects in light of the lessons learnt from past mistakes. The Aral Sea crisis[80] is a grim reminder of the severe

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further reading on the topic [8]. Jain et al. (2006) also discussed some of the major issues surrounding the project.

78 After the water level in Dalai Lake has dropped, it was proposed to divert water from the Hailaer River to Dalai Lake. The environmental concerns include loss of habitat, pollution of the Hailaer River and the adverse effects on the population downstream of the point of diversion. [17]

79 Water from the Great Lakes is diverted to provide water for municipal, industrial and irrigation use in Chicago, Detroit, London and Ontario. The water from the Great Lakes also supports shipping and recreational boating in Illinois, Wisconsin, Ohio and New York, and hydroelectric power production in Ontario. With the increasing population and the declining levels of groundwater in several parts of the United States, there is a growing need for the conservation of the Great Lakes water.

The possibility of future trading of water from the Great Lakes is another concern. The Green Party of Canada has reported the following on its website - According to the leaked minutes of a 2004 meeting of the Task Force on the Future of North America, which led to the SPP: "No item, not Canadian water, not Mexican oil, not American anti-dumping laws, is off the table."
(Canada, the United States and Mexico are members of the Security and Prosperity Partnership (SPP) of North America, which came into being on March 31, 2005 to advance free trade and security cooperation.) [11]

In the context of water trading in the future, the following (slightly unsettling) prediction by Rees-Mogg (2007) was published on MoneyWeek magazine's website:
"There are countries that have an over-abundance of water – and here there are opportunities for sale to other countries. Canada, for example, has the same amount of water as China, but just 2.3% of its population. Brazil has far less need of its water than many of its neighbours. As the value of water rises, countries like these will start to export their spare reserves to those more in need – and willing to pay. Pipelines will spring up, connecting states and countries. Tankers will transport water across the sea as often as they do oil. Water will be on the move. And those who can transfer it will be there to benefit."
Perhaps it is time we asked ourselves: Is water the next oil?

80 The Aral Sea is a saline endorheic lake (having no outflow). In the1940s, the Amu Darya and Syr Darya rivers, which used to feed the Aral Sea, were diverted to irrigate cotton fields in Uzbekistan, Turkmenistan and Kazakhstan. Although the region saw a brief period of prosperity and improved living conditions, there were severe environmental, health and socio-economic repercussions. The land and water in that area is

health, environmental and socio-economic consequences of the mismangement of transboundary water. The loss of habitat in the Colorado River Delta basin[81], the shrinking of Lake Chad[82], the increase in groundwater salinity in the Sfax Basin (Tunisia)[83] – these are all cautionary examples of the negative impacts of anthropogenic stressors on natural ecosystems.

Besides the environmental considerations, water management issues involve political complexities as well. Several water bodies span across the boundaries of neighbouring nations (e.g, the Colorado and Rio Grande river (the Americas), the Euphrates, Nile, Jordan rivers (Middle East), the Brahmaputra, Indus, and Ganges rivers (South Asia)). These shared water resources can be sources of national and international conflicts. In the United States, legal conflicts between

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contaminated with pesticides. The salt from the exposed lake floor, contaminated with toxins, gets carried with the wind. The surrounding region has an alarmingly high occurrence of liver, kidney and respiratory diseases, infant and maternal mortality rates. Most of the health problems can be attributed to the toxic dust storms. As the natural water cycle was disturbed, the winter rains in the region have become increasingly rare, leading to acute shortage of fresh water in the region. This man-made 'eco-disaster' also resulted in massive changes in the regions climate (Micklin (1988), Vitousek, et al. (1997), Badescu, (2010)).

[81] The construction of the Hoover Dam (1932) damaged the ecosystem of the Colorado River Delta basin. The loss of the natural wetland habitat caused a decline in the wildlife, which in turn affected the native people in that region (Glenn et al., 2001).

[82] Similar to the Aral Sea, Lake Chad is a saline endorheic lake. The main rivers flowing into the lake are the Yedesram/Ngadda and Hadejia Jama'rare-Komadouguo/Yobe from northeast Nigeria, and the Logone and Chari rivers from the southwest Chad. Much of the shrinking of Lake Chad is due to natural desertification and the arid conditions in the region. However, human activities, (especially irrigation) exacerbated the desiccation of the lake ["Lake Chad: A Study of a Drying Freshwater Body", Guardian Newspapers (date unknown), Coe and Foley (2001)].
Ironically, one of the definitions of the word 'Chad' in the online dictionary Dictionary.com is as follows: African nation, former Fr. colony (Tchad), independent since 1960, named for Lake Chad, from a local word meaning "lake, large expanse of water."

[83] Due to unsustainable irrigation practices in the Sfax Basin in Tunisia, the water table has fallen and the use of saline water for irrigation has resulted in elevated groundwater salinity and soil salinization. (Trabelsi et al., 2007). (The authors have not quantified the decrease in the level of the water table.)

Kansas and Nebraska[84] have resulted over water issues. The Brahmaputra River[85] has been a cause for strained diplomatic relations between China and India for several years. The Bakassi Peninsula has been a disputed territory between Nigeria and Cameroon[86] for decades. These conflicts indicate that the policies involving water management should be formulated with a broader perspective that takes into account the existing diplomatic relationships and the potential conflicts that could result from water insecurity. The national and international biofuel programmes must also consider the spatial mismatch between availability and demand of water within nations and across the globe. As jatropha cultivation is being actively pursued in Africa, such considerations are especially important there, because many parts of the continent experience acute water shortage and conflicts may result from water insecurities, given the volatile political atmosphere.

It is important to increase the production of biofuels and gradually wean the world from conventional fossil fuels. At the same time, it is vital to carefully evaluate the the water consumption involved in producing biofuels. While the search for clean

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[84] According to the U.S. Water News online (June 2008): "Kansas contends Nebraska used about 80,000 acre feet, or roughly 26 billion gallons, more than it was allowed in 2005 and 2006. It has demanded more than $72 million for the overuse in addition to a shutdown of wells that irrigate nearly half of the 1.2 million acres in Nebraska's portion of the river basin." [10]

[85] The river water diversion projects in south China and a feasibility study of the construction of a hydropower plant along the section of the Brahmaputra River flowing through the Chinese territory raised concerns about the water security in the north eastern parts of India. After denying the existence of such a project for several years China has recently admitted that it is building a hydropower plant along the Brahmaputra River. The effect of this project on the Indo-Sino relationship remains to be seen [38].

[86] The Bakassi Peninsula has been a disputed territory between Nigeria and Cameroon for decades. Water fisheries, the presence of potential oil reserves are the primary reasons for the conflict (Price 2005).

and renewable alternatives to fossil fuels gathers momentum, we must also ensure that the drive for biofuels does not clash with the goal of providing safe and clean water to the growing world population.

Food vs. Biofuels: The effect of biofuels on food prices and the agricultural industry

Several researchers have questioned the sustainability of food-based biofuels (e.g., Fitzherbert et al. 2008, Nelson and Robertson 2008, Pimentel et al. 2009, Scharlemann and Laurance 2008). However, the most severe criticism against these biofuels is due to their potential negative impacts on food security. The use of biofuels is believed to compete with food for resources (e.g., land, water, labour) and exacerbating world hunger (e.g., Pimentel 2009, Abbott, Hurt and Tyner 2008, Leibtag 2007). At this time, when over a billion people in the world are malnourished[87], it is important to address the socio-economic and ethical issues pertaining to the use of biofuels vis-à-vis global food prices and re-evaluate the sustainability of biofuels in the context of food security. Analysing the impact of the U.S. corn-based ethanol industry on national and global food prices and on the agricultural industry can shed some light on these issues, since the use of jatropha is not sufficiently widespread to conduct such an analysis.

In 2007, the inflation in food prices in the United States was twice that of the overall inflation (Henderson 2008). The price of corn rose from $2.55 (per bushel) in 2005 to $4.04 in 2007 (Hagenbaugh 2007)[88] at the same time when corn

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[87] In 2009, the Food and Agricultural Organisation (FAO) has estimated the number of undernourished people worldwide to be 1.02 billion [6].

[88] Leibtag, (2008) has reported the price rise as $2 per bushel in 2005 to $3.40 per bushel in 2007. (Runge and Senauer (2007) have mentioned in their report that in March 2007, the price of corn rose to over $4.38 a bushel.

production in the U.S. reached record values[89]. The rising demand for corn[90] in the ethanol industry is said to have caused this inflation[91] in the price of corn, which in turn increased the price of corn-based retail food. However, other factors (e.g., processing and packaging) in the manufacturing process of retail food dampened this price rise to some extent. Apart from the 'farm value'[92] of corn, the extent of processing involved and value added services (e.g., advertising and packaging) also contribute to the final price of corn-based retail food items (Leibtag, 2008)[93]. While the price of corn rose, the cost of the value added services did not change as much. Therefore, the price of retail food increased to a smaller extent as compared to the increase in the price of corn[94].

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89 The corn production in 2007 was 13.1 billion bushels. The previous record was 11.8 billion bushels in 2004 (U.S. Department of Agriculture's National Agricultural Statistics Service (NASS))

90 In late 2006 in Mexico, the price of tortilla flour doubled due the rise in U.S. corn prices from $2.80 to $4.20 a bushel. (Runge and Senauer, 2007).

91 Ethanol production in the United States was almost 5 billion gallons in 2006. This was about 1 billion gallons more than in 2005 (Westcott, 2007).

92 i.e., the commodity cost or price per bushel

93 Although value added services have had a dampening effect of on the food prices, the cost of such services has risen in the past few decades, adding to the increase in food price. Their effect, however, has been more gradual. Henderson (2007) has mentioned that marketing costs ("the difference between the farm value and consumer spending for food at grocery stores and restaurants") have risen from fifty-nine percent of the total retail food price in the 1950s to sixty-seven percent in the 1970s to eighty percent today.

94 Leibtag (2008) has made the following estimate: "Currently, about 4.1 percent of U.S.-produced corn is made into high-fructose corn syrup. A 2-liter bottle of soda contains about 15 ounces of corn in the form of high-fructose corn syrup. At $3.40 per bushel, the actual value of corn represented is 5.7 cents, compared with 3.8 cents when corn is priced at $2.28 per bushel. Assuming no other cost increases, the higher corn price in 2007 would be expected to raise soda prices by 1.9 cents per 2-liter bottle, or 1 percent. These are notable changes in terms of price measurement and inflation, but relatively minor changes in the average household food budget."

Fifty to sixty percent of the corn produced in the U.S. is used as animal feed[95] (Westcott 2007). Higher corn prices affect the livestock sector by reducing the profit margins for the meat, poultry and dairy industries. Thus the price rise of corn has a ripple effect on the price of meat, eggs and dairy products. Moreover, manufacturing these food items involves much less processing and value added services as compared to other retail food items (e.g., corn-based cereals and high fructose corn syrup based beverages). Hence, the price of meat and eggs is more sensitive to the increase in the price of corn.

As mentioned before, the price of retail food in the U.S. depends on several factors (besides the commodity price of corn), which coupled with the competition between retailers, have a stabilizing effect on the food price. However, the effect of the use corn-derived ethanol on the price of food in developing nations is far more drastic. The citizens in the developing nations consume less processed food than those in the industrialized nations. Low cost grain is a dietary staple in the developing nations. Therefore, the food prices in the import-dependent developing countries are more closely tied to the commodity price of corn[96]. The highest occurrence of world hunger is in the countries in Asia and the Pacific

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[95] Distillers grains, a coproduct of dry-mill ethanol production, can be used as livestock feed. Ruminant animals, such as beef and dairy cattle, can readily use distillers grains. However it is less suitable for monogastric animals, (e.g., hogs and poultry) (Westcott, 2007).

[96] About forty percent of the world's total corn is produced in the U.S. (Runge and Senauer, 2007). Between 2003 and 2008, the average share of the U.S. in the total corn exports averaged sixty percent (USDA).

region and Sub-Saharan Africa[97]. Increasing food prices will exacerbate the dire situation in these nations. One of the causes of increasing food prices and growing world hunger can be traced back to corn-based biofuels[98].

In addition to directly affecting food prices, the increasing demand for corn for ethanol production has indirect effects on the agricultural industry. The impact of ethanol on the agricultural industry is comparatively large, as compared to its share in the overall gasoline market[99]. Due to the growing profitability of corn production, farmers are increasing the acreage allocated for corn at the cost of other crops. As the cultivation of other food crops is reduced, their prices increase as well, because the demand for those food crops does not decrease. However, indiscriminately increasing the acreage for corn cultivation will have a detrimental effect in the long term. In the U.S., corn is typically planted in rotation with soybean (Runge and Senauer 2007, Westcott 2007). Soybean, being a leguminous plant, fixes nitrogen, which helps in maintaining the soil fertility. Increasing the frequency of corn cultivation at the cost of soybean will result in

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97 The number of undernourished people in different parts of the world in 2009 is as follows:
Sub-Saharan Africa: 265 million
Asia and the Pacific: 642 million
Latin America and the Caribbean: 53 million
Near East and North Africa: 42 million
Developed countries: 15 million [5]

98 To put things in perspective, Runge and Senauer (2007) said:
"Filling the 25-gallon tank of an SUV with pure ethanol requires over 450 pounds of corn - which contains enough calories to feed one person for a year."

99 In 2006, ethanol represented about 3.5 percent of motor vehicle gasoline supplies in the United States. However, about 14 percent of corn use went to ethanol production in the 2005/06 crop year (Westcott, 2007). "Even if the entire corn crop in the United States were used to make ethanol that fuel would replace only 12 percent of current U.S. gasoline use." (Runge and Senauer, 2007)

the depletion of nitrogen from the soil. Hence, to maintain soil fertility and increase corn yields, large amounts of fertilizers would be required. The cultivation of corn (a row crop) contributes to soil erosion. This, coupled with the higher usage of fertilizer, would increase water pollution due to agricultural runoff[100].

The problem of water pollution by agricultural runoff has another component to it. The conservation reserve programme (CRP)[101] pays farmers for not cultivating those lands that are highly susceptible to soil erosion. As corn prices rise and increasing the acreage for corn cultivation becomes more profitable, the number of farmers enrolling in this programme will decrease[102]. Increasing row crop plantation on erodible lands exacerbates problem of water pollution by agricultural runoff. This also affects the measures for conservation by undermining the efficacy of the CRP.

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100 The Gulf of Mexico and the Gulf of Trieste (Northern Adriatic Sea) (Italy-Croatia) are examples of water bodies polluted by nutrient runoff (Diaz, 2001).

101 The Conservation Reserve Program (CRP) is a voluntary programme in which agricultural landowners receive annual rental payments and cost-share assistance to establish long-term, resource-conserving covers on eligible farmland.
CRP protects agricultural lands from topsoil erosion and mitigates groundwater and surface water pollution by reducing agricultural runoff. By mandating the plantation of resource-conserving vegetative covers the CRP also contributes to increased wildlife populations [2].

102 The CRP contracts for 874722 acres expired in 2005. Only 318559 acres were reenrolled the next year. In 2006, contracts for 686805 acres expired and only 241050 acres were reenrolled in 2007. The numbers were obtained after summing the acreage enrolled in each state in the U.S. [4]. The typical duration of the contracts is ten to fifteen years. According to the March 2010 CRP contact status report, the contracts for 4.4 million acres are scheduled to expire in 2011, 6.5 million acres in 2012 and 3.3 million acres in 2013. It remains to be seen what fraction of these lands are reenrolled into the programme [3].

The increasing demand of corn for ethanol production has resulted in lower annual ending stocks of corn. Lower carryover stocks of corn are maintained to meet this increasing demand. This makes the agricultural prices more volatile and susceptible to market fluctuations (e.g., reduced production due to drought and loss of crop yield due to infestation by pests).

Besides ethanol, the production of biodiesel from food crops other than corn (e.g., soybean, sunflower, cassava) also contributes to increasing food prices. According to the estimates by the International Food Policy Research Institute (IFPRI), the prices of oilseeds are projected to rise by 26% by 2010 and 76% by 2020. The price of cassava[103] is expected to increase by 33% by 2010 and 135% by 2020.

In light of the evidence of the contribution of food-based biofuels to escalating food prices, it is important to switch to alternative feedstock for biofuel production. While second-generation biofuel feedstock (e.g., microalgae and switchgrass) hold the promise of sustainable biofuels without competing with food crops, the technology for second-generation biofuels is still in its infancy. In

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[103] Runge and Senauer (2007) have stressed on the potential problems with biofuels from cassava. "The production of cassava-based ethanol may pose an especially grave threat to the food security of the world's poor. Cassava, a tropical potato-like tuber also known as manioc, provides one-third of the caloric needs of the population in sub-Saharan Africa and is the primary staple for over 200 million of Africa's poorest people. In many tropical countries, it is the food people turn to when they cannot afford anything else. It also serves as an important reserve when other crops fail because it can grow in poor soils and dry conditions and can be left in the ground to be harvested as needed"… "The likely result of a boom in cassava-based ethanol production is that an increasing number of poor people will struggle even more to feed themselves."

this scenario, it is worthy to look at jatropha as a potential energy crop that does not compete with food crops.

If jatropha is grown in areas that are not suitable for food crop production, there is no danger of jatropha-based biofuels displacing food crops. However, if the future market prices for biofuels continue to rise, farmers might find it more lucrative to switch from food crops to jatropha or other energy crops. In such cases, the governments in those nations would need to offer appropriate monetary incentives to farmers to maintain food crop cultivation.

In a report published by the International Food Policy Research Institute (IFPRI) (Braun and Pachauri 2006), the authors mention that the concerns and insecurities related to food production can be laid to rest by the effective use of degraded and "wastelands" for biofuel production, while reserving "favourable" (more fertile) lands for food crops. The report also cites the example of jatropha as a promising source of biofuel feedstock in wastelands and for achieving a "sustainable balance" between biofuels and food crops[104]. While the authors' suggestion to use wastelands for jatropha cultivation is sound, the possibility of jatropha competing with other food crops for other resources (e.g., water, labour, agrochemicals) cannot be ignored. Also, the cultivation of jatropha or other plants

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[104] The report mentions the following plans for jatropha based biodiesel programme in India: "India has 60 million hectares of waste land, of which it is estimated that half might be used for Jatropha cultivation. The cost of producing biodiesel from Jatropha is just Rs. 20–25 (US $0.43–US $0.54) per liter. The Energy and Resources Institute (TERI) of India announced in February 2006 that it is undertaking a 10-year project, in conjunction with BP, to cultivate 8,000 hectares of wasteland with Jatropha and install the equipment necessary to produce 9 million liters of biodiesel a year. The project will include a complete analysis of the social and environmental impacts of the approach." (Braun and Pachauri 2006)

on marginal lands is likely to require more fertilizers and other agrochemicals than on more fertile lands. This would increase the potential for eutrophication and diminish the GHG savings.

Braun and Pachauri (2006) mentioned that besides the lack of availability, food insecurity is also closely related to poverty, as the "food-insecure" sections of the population cannot afford to buy food even if it is available. In this context, can biofuels generate employment and improve food security? Unfortunately, the relationship between poverty, hunger, food prices and biofuels is not that straightforward. Most of the world's poor depend on agriculture for subsistence. From this, it is tempting to conclude that higher commodity prices could raise their income levels, allowing them to improve their living standards. But a deeper look at the issue of rising commodity prices for corn shows that this is not true. While increase in the commodity price may help the agricultural landowners, the landless rural population stands to suffer[105]. In this scenario, biofuel feedstock cultivation (e.g., jatropha) could potentially generate employment for the landless and poor sections of the population and help to mitigate food insecurities.

Although several factors (e.g., the rise in crude oil prices (Henderson 2008), the weakening of the U.S. dollar (Abbott et al. 2008), adverse weather events[106]

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105 Unless they are offered food security by their governments, NGOs or humanitarian organizations, the unemployed landless poor population in the developing nations, they are likely to suffer at least in the short term, before the efforts to make food more affordable and accessible bear fruit.

106 In the year 2007, droughts in southeast Europe, northwest Africa, Turkey and Australia, freeze in the U.S. and Argentina and floods during the time of harvest in Northern Europe also contributed to higher food prices (Trostle, 2008).

(Trostle 2008) have contributed to escalating food prices, it cannot be denied that food-based biofuels have aggravated food insecurities as well. The situation is likely to worsen in future, given the aggressive drive for biofuels. Therefore it is recommended to switch to alternative, second-generation feedstock to avoid any competition between food and biofuels. However, discontinuing the use of food-based feedstock alone will not solve the problems associated with food insecurity and hunger. The primary solution to eradicate world hunger is the development and implementation of novel technologies for improving crop yields. Biotechnological advancements for disease-resistant high-yielding crops, engineering solutions for optimized agricultural practices and the sustainable use of the available resources of land and water will ensure that the global food prices are decreased and food insecurities are mitigated.

Biofuel Policies: Social and Ethical Issues[107]

As mentioned in the previous chapter on the food-biofuel conflict, food-based biofuels have contributed to increased food prices and have exacerbated food insecurities (e.g., Pimentel 2009, Abbott, Hurt and Tyner 2008, Leibtag 2007, de Fraiture, Giordano and Liao 2008). However, sustainable policies and programmes that promote non-food-based biofuels can create jobs, increase income levels and help to improve food security in the developing world (e.g., Pingali, Raney and Wiebe 2008, Pinzi et al. 2009, Braun and Pachauri 2006). Tropical climates are well suited for the growth of energy-rich biomass. If the technological challenges of biofuel production can be overcome, many developing nations, with the advantage of favourable climate can become major exporters of biofuel. The cultivation of biofuel feedstock requires the investment of resources such as land, water and labour. In the case of jatropha, diverting these resources from their existing uses to use in large-scale feedstock cultivation would be a risky endeavour, due to the lack of reliable data regarding yields, the uncertainty in the water requirements and the overall sustainability. Achten et al. (2010) proposed the propagation of jatropha on a small scale in rural areas before cultivating it in on a larger scale. In fact, the most promising social benefit of biofuels is the potential upliftment of rural societies, especially in underdeveloped nations. If biofuel programmes are implemented wisely while protecting the interests of the local population, land-owning farmers and the

[107] The chapter addresses some social and ethical issues pertaining to biofuels and their related policies. While the issues involve biofuels in general, they are also applicable to jatropha-based biodiesel.

landless population, both stand to gain[108]. Besides generating employment, biofuels can help rural communities become self-sufficient in terms of their own energy needs[109]. The newly created jobs in the biofuel sector can also mitigate rural depopulation[110] both in the developing and the industrialized nations.

While the labour intensive cultivation process can result in employment opportunities, the mere generation of jobs does not automatically guarantee improved livelihood and living conditions. It must be ensured that the new jobs meet national and international standards. Living standards are dependent upon both economic factors (e.g., wage, bonus) and non-economic factors (e.g., healthcare[111], education, empowerment of women in rural societies). Besides

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108 In jatropha cultivation, the fruits are harvested only after they mature. Since the fruits do not mature at the same time and because agriculture is not mechanized in developing nations, cultivation of jatropha (especially harvesting) very labour intensive. This demand for labour holds the promise of job creation and raising income levels in rural communities. Agricultural landowners can benefit from the revenue generated by feedstock (e.g., jatropha) cultivation. The poor and landless sections of the rural population can be employed in the various stages of the biofuel production process (e.g., cultivation, harvesting, transport, oil refining and distribution).

109 Raw jatropha oil can be used in stoves, lamps and for running agricultural machinery (e.g., pumps, mills and small generators) that currently use other fossil fuels. Byproducts of jatropha cultivation such as seed husks can be used for combustion and gasification. In small-scale decentralized systems, the farmers will have access to the seedcake, which can be used as a natural fertilizer (Achten et al., (2010). However, the combustion products of jatropha oil must be analysed to ensure that using jatropha oil indoors for cooking and lighting is safe.

110 In their studies on the depopulation of several rural counties in the U.S., Walser and Anderlik (2004) have described the phenomenon to be "...a self- reinforcing cycle of decline: declining populations lead to decreased economic vitality, and both lead to higher per capita costs; the higher costs provide incentives for continued out- migration – and the downwardly spiraling quality of life and of the supporting infrastructure in these counties makes it increasingly difficult for the counties to attract new businesses to the area."

111 Healthcare benefits are especially pertinent in the context of jatropha. In developing nations, seed picking will most likely be done by hand, because most agricultural procedures (e.g., harvesting) are not mechanized. Since phorbol esters in jatropha seeds are known to be co-carcinogens and tumour promoters (Makkar et al.(1998), manual seed picking is carries potential health risks which merit careful consideration. Also, as phorbol esters are a part of the extracted oil and the seedcake, measures should be

generating rural income, biofuel programmes must address these non-economic factors as well.

In theory, biofuels may be beneficial for rural societies in developing nations. However, due to the varying challenges involved in the production of biofuels and the constraints regarding the availability of resources, it may not be possible to implement sustainable biofuel programmes in some countries. Land is the most important resource for expanding agricultural areas and accommodating feedstock cultivation. Sustainable biofuel production may not be possible in land-scarce, low-income and food insecure nations (e.g., Bangladesh) that lack both the resources and the infrastructure for further agricultural expansion. Low-income countries that have abundant unused land resources but lack the infrastructure (e.g., Tanzania) will rely heavily on foreign investments to develop new markets for biofuels. However, there are dangers of land rights violations in such nations if appropriate polices are not implemented. Therefore, national policies on biofuels must safeguard the interests of the rural communities. National and local authorities must ensure that the land rights of the local population are protected while allocating or leasing the land for feedstock cultivation. This is especially pertinent when large corporations[112] are involved in the biofuel programmes in developing nations, where the rights of the rural poor

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taken to avoid contact with the oil after extraction and in the downstream processes involved in biodiesel production.

[112] Daimler Chrysler has been involved in India's jatropha programme. The Council of Scientific and Industrial Research (CSIR, India), Daimler Chrysler and the University of Hohenheim (Germany) are working in collaboration on a biodiesel project in India [77].

are seldom well protected[113]. On ther other hand, sometimes, well meaning national policies may have unintended consequences, where short-term economic benefits may be followed by negative social and environmental impacts in the long term. An example of such an issue is the resettlement of a section of the population in Laos[114] due to a change in the agricultural policies that resulted in improved living conditions in the short-term followed by severe land degradation in the long term. Therefore, before implementing new policies, the future impacts should be carefully assessed, while actively engaging the local communities. Perhaps, the situation in Laos could have been avoided by involving the local farmers who would have known that sustainable agricultural

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113 While palm oil cultivation is considered to be a boon for the economies of Malaysia and Columbia, the violation of land rights of the local farmers in these countries are examples of social injustice in the name of growth and development. (Ayob and Yaakub (1992), Colombia palm oil biodiesel plantations: A "lose-lose" development strategy (2008))

114 Between 1975 and 1977, sections of the population in the highland areas in Laos were resettled in the Ban Lak Sip village. The reasons behind the resettlement were 1) to make the medical and educational services more accessible 2) to change the agricultural system from a subsistence-centric, shifting cultivation (practiced in the highland areas) to a more stable, market-oriented system.
Later, the Land Use Planning and Land Allocation (LUPLA) programme was introduced in 1989. According to the new policies in the programme, each household in Ban Lak Sip was allotted three plots of land for farming. (The size of the plots was not specified in the original report.) Agriculture was banned on the remaining land surrounding the village. This land was later classified as 'production forest' (the use of which was limited to hunting, collection of forest products, and timber extraction). The highland areas were classified as 'protection forests'. These protection forests were intended to reduce soil erosion and for environmental conservation.
Initially, the policies had the desired effects. Forest cover increased in the depopulated areas. Medical and educational services became more accessible. Livestock production improved. Teak and banana cultivation and vegetable cultivation increased. However, there were unforeseen impacts that resulted in severe land degradation in the area.
Limiting the land available for agriculture created an artificial land shortage. The farmers were forced to double the cultivation period and shorten their fallow periods to meet their requirements. This resulted in the rapid deterioration of the land due to the new and unsustainable agricultural practices. As yields reduced, the farmers were forced to reduce the fallow periods even further, thereby hastening the downward spiral of declining soil quality and crop yields. Thus, in the long term, the policies had the opposite effect of what was originally intended. (Lestrelin et al., 2005)

practices would not be possible, based on the new agricultural policies that were being introduced by the government.

International policies on biofuels have a significant role to play in the development of new biofuel markets. Until the technology for biofuel production is transferred from the developed nations, the primary role of the developing countries would be that of biofuel feedstock exporters. In fact , biofuel feedstock could be the major export for many developing nations. The economies of developing nations are uniquely sensitive to policies made in the industrialized nations. A look at the Philippines' economy vis-à-vis the sugar industry is a valuable example of how changes in international policies can affect a nation's economy. Sugar was Philippines' leading export crop, with most of the sugar production exported to the United States. The Jones-Costigan Act (1934) and the Sugar Act (1937) resulted in a duty free quota system for sugar imports in the United States. In 1955, the Laurel Langley Trade Agreement was signed, by which the Philippines were granted a high quota for sugar exports to the U.S. until 1974. As the trade relations between the United States and Cuba deteriorated following the Cuban Revolution (in 1959), the quota of all other sugar exporting countries was increased. In 1961, the Philippines received fifteen percent of Cuba's previous share of sugar exports to the United States.

Later, when the U.S. beverage industry switched from sugar to high fructose corn syrup, there were reductions in the quota allotted to sugar exporting countries. The Philippines then had to sell sugar to the world market and had to compete with sugar beet[115] producing countries. As sugar was highly subsidized in the world market, this made the competition even stiffer.

These factors, coupled with the fluctuations in sugar prices caused the Philippines' sugar industry (hence, the local economy) to be adversely affected. Sugar prices plummeted from more than 60 cents (U.S.) per pound in 1974 to less than 3 cents (U.S.) per pound in 1985, leading to an economic crisis in the Philippines (Anunciacion 1962, Honda 1996, Bergsma et al. 2007). This also led to unforeseen social and environmental impacts[116]. As sugarcane cultivation was no longer a source of viable income, sugar plantation owners were forced to abandon their sugarcane fields and migrate to other areas. Previously, large areas of forestland had already been cleared for sugarcane plantation. This, coupled with the abandoned plantation sites added to the existing problems of deforestation, soil erosion and loss of biodiversity, thereby severely affecting the terrestrial ecosystem .

With "greener" biofuels from second generation feedstock promising improved GHG performance, similar concerns regarding the economies of developing nations would be raised in those developing nations, where jatropha-based

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[115] Sugar beet is a root crop, which grows best in temperate climate. A vast majority of sugar beet is grown in the developed nations (e.g., Europe and North America) where agriculture is highly mechanized and agricultural technologies are more advanced. So, in the world market for sugar, developing nations like the Philippines are in direct competition with the developed nations. (Anunciacion 1962, Honda 1996, Bergsma et al. 2007)

[116] Since the 1950s, the watershed area around Ormoc had been planted with sugarcane, which does not absorb flood waters (Anunciacion 1962, Honda 1996, Bergsma et al. 2007). The floods in Ormoc (1991), which resulted in over 5000 deaths, underline the severity and seriousness of deforestation.

biofuel programmes are being implemented, if later on, another plant is favoured over jatropha as a biofuel feedstock. Biofuel programmes and biofuel-related policies must ensure that the transition from one feedstock to another is gradual while allowing the agricultural sector to adapt to the change. For example, if the biofuel industry in the U.S. were to suddenly switch from corn to switchgrass or microalgae, corn prices would plummet and there would be severe financial consequences in the agricultural sector. Therefore policies which safeguard the fragile and budding economies (especially those in parts of Africa) should be formulated and periodically evaluated. In addition to the influences of external policies and market fluctuations, internal policies and laws (at state and national level) and the volatile political climate in some parts of the world (e.g., Africa) should be taken into consideration.

As mentioned in the chapter on LCA, soil organic carbon plays a vital role in the quality of soil (hence yield). Jatropha-related biofuel policies should be extended to account for not only land-use changes, but also carbon emission and sequestration. The farmers should also be educated with regards the role of soil carbon in agriculture, and the impact of soil carbon on the overall soil quality and crop yields. The knowledge that proper recommended management practices (RMPs) in agriculture can help in increasing the soil organic carbon content (and ultimately the yield) would provide the necessary incentive for the farmers to practice sustainable cultivation, focussing on crop yield as well as carbon balance.

Agricultural policies for feedstock cultivation must also safeguard against extractive agriculture and soil-degrading practices. Extractive agricultural practices do not replenish the soil nutrients and have the detrimental effect on the soil quality and crop yields in the long term (Vågen, Lal and Singh, 2005). An example of such agricultural practices would be the cultivation on corn as monoculture with reduced fallow periods and without rotation with a nitrogen fixing plant (e.g., soybean). Unsustainable practices and soil carbon depletion in Sub-Saharan Africa have resulted in severe soil degradation and desertification, resulting in continuous food shortage, poverty, hunger and substandard living conditions. Hence agricultural policies should be extended to minimize and eliminate nutrient depleting and extractive cultivation, while encouraging practices that result in soil restoration and overall soil quality improvement (Vågen, Lal and Singh 2005, Lal 2004).

As mentioned in the previous chapter, ethanol production from corn contributes to escalating food prices. Therefore national policies in the U.S should be revised to reduce the existing subsidies for corn cultivation and instead, focus on the research for non-food based second-generation feedstock (e.g., switchgrass, microalgae) which may also offer improved GHG balance as compared to corn based ethanol (Schenk et al. 2008, Gouveia and Oliveira 2009).

The agricultural stage of biofuels production is the most resource consuming step and may initially involve a carbon debt when unused land is tilled. Moreover, the biofuel production processes also involve GHG emissions. Some countries may become exporters of biofuel feedstock, some both importers of feedstock and exporters of the finished product (i.e., biofuel) while others may simply be importers of the finished product. In such cases, it would be essential to account for the individual countrie's contribution to the net GHG emissions and carbon debt. Therefore, international authorities mandating laws on carbon emission must ensure that such carbon debts and GHG emissions are appropriately 'shared'[117] by the *producer* countries as well as the *consumer* countries.

Besides several economic and social factors, the subject of biofuels and their related policies have an ethical angle as well. This is primarily due to the fact that biofuels are, in some ways, responsible for excaberbating food insecurity. Knowing that there are a billion hungry people in the world, it is tempting to be swayed into thinking that biofuels are a scourge of the society and that the debate of "Food vs. Biofuels" pitches the affluent, SUV[118]-drivers against the impoverished millions[119]. Therefore a balanced and rational approach to this debate is essential. Switching from corn to non-food based biofuels will mitigate the turf war between food and biofuels. It is also important to increase public

[117] Based on the GHG emissions in different stages of biofuel production, different indices may be assigned and the net 'share' of the carbon debt may be allocated. (Smith, 1991) suggested the use of a 'Natural Debt Index' to allocate the 'responsibility' of global warming to different countries.

[118] Sport utility vehicle

[119] de Fraiture et al. (2008) mentioned "Malnourishment occurs because of lack of access to food rather than global food shortage." Citing that in the developing nations, the commonly food crops used in biofuels (e.g., sugarcane, corn and maize) are either used primarily as animal feed (corn and maize) or as cash crops (e.g., sugarcane), the authors have proposed that the effect of biofuels on the price of meat and eggs is more pronounced than on the price of food grains. ("Globally 65% of all maize is used to feed animals; in the USA it reaches 75%.", de Fraiture et al., 2008). Hence, the authors have concluded that the "unfolding global conflict over food" – as eloquently coined by Brown (2006) – may not be between cars and the poor as he [Brown] envisions, but rather between cars and carnivores."

awareness about the emerging technologies related to biofuels and the steps being taken to improve food security. Governments, NGOs and local authorities have a responsibility to make the scientific information related to the biofuels available to the public and raise public awareness regarding issues and trends related to the sustainability of biofuels. While the news media is responsible for portaying biofuels in an unbiased light, the public also has a responisibility for choosing reliable, scientific and responsible sources for biofuels-related news, while questioning and participating in the discussions on the biofuel policies and critically evaluating the information provided, before forming any opinion on the matter of biofuels.

Recommendations:

The biofuel industry is poised for rapid growth to meet the growing energy demands of the world (e.g., McCormick et al. 2009, Sims et al. 2010). At the same time, there are growing concerns regarding the environmental impacts and the overall sustainability of biofuels (e.g., Searchinger et al. 2008, Hill et al. 2006, Scharlemann and Laurance 2008, Pimentel and Patzek 2006). Also, there is evidence suggesting that biofuels have contributed to increasing food prices (e.g., Henderson 2008, Abbott, Hurt and Tyner 2008, Armah, Archer and Phillips 2009). Despite these concerns, it cannot be denied that the proper management of biofuels can have environmental and societal benefits. Researchers and policymakers must focus on several areas of improvement with regards to biofuels and harness potential advantages. Some areas for improvement are identified and the potential solutions are discussed in this chapter. While some recommendations are made for jatropha-based biodiesel, they also apply to biofuels in general.

At present, biofuels are being promoted mainly to replace fossil fuels in the transportation sector. At the same time, the broader applications of biofuels to meet household and industrial energy needs must not be ignored. Biofuels may potentially be used for indoor heating in place of conventional fuels such as propane. Clean burning biofuels may also replace liquefied petroleum gas (LPG) as cooking fuel. Until large-scale production of biofuels becomes a reality, resulting in significant reductions in fossil fuel consumption in the transportation sector, it is suggested that biofuels be promoted for use in households and small-scale commercial establishments.

While there are unanswered questions regarding the sustainability of large-scale biofuel production, promoting feedstock cultivation on a small-scale (community level) can be beneficial. Biofuel feedstock cultivation can generate employment and help rural economies, especially in the developing nations. This is especially true for jatropha cultivation in the underdeveloped nations with favourable climatic conditions. It is therefore recommended to promote jatropha on a community level to evaluate its sustainability on a smaller scale. This can help the local population become self-sufficient and meet its energy requirements by using raw jatropha oil for cooking, lighting and in agricultural machinery. It is also recommended that combustion byproducts of jatropha oil be analysed to ensure that oil is safe to use indoors.

The idea of using jatropha for biodiesel production on smaller scale also raises the question: Is it more beneficial to pursue biofuel production from different feedstock in different regions of the world?[120] Due to the varying climatic conditions across the world, it seems unlikely that a single energy crop can produce high yields everywhere and meet the local and global fuel requirements. Therefore it would perhaps be beneficial for different regions of the world to use

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[120] Tilman et al. (2009) have discussed the use of five potential biofuel feedstock - 1) perennial plants grown on degraded lands, 2) crop residues, 3) sustainably harvested wood and forest residues, 4) double crops and mixed cropping systems and 5) municipal and industrial wastes. However, there are technological challenges for large-scale biofuel fuel production from these feedstocks.

suitable indigenous plants as biofuel feedstock based upon climate, availability of technology, and the feasibility of maintaining sustainable biofuel programmes.

This brings us to the issue of the sustainability of biofuels. Lifecycle assessment (LCA) studies are the primary source of information regarding biofuels' sustainability. However, due to the assumptions made by the researchers and the site- and process-specific nature of most studies, comparative analyses of LCA studies are not always possible. The primary areas of concern are the inconsistencies in the use of functional units, the difference in the efficiencies of various processes, the ambiguities in defining the system boundaries and the authors' subjectivity regarding the inclusion or exclusion of various components from the lifecycle inventories (LCIs). Therefore, there is an urgent need to standardize[121] the procedures for LCA and incorporate more uniformity in future LCA studies. LCA studies must also quantify the sensitivity to various parameters (components in the LCIs) and should include recommendations for optimizing the most influential parameters. Identifying the most important components of LCIs will make the definitions of system boundaries more homogeneous in later studies. The development of improved models[122] that predict the lifecycle behaviour of a biofuel feedstock in a given set of conditions (soil type, rainfall, climate etc.) using the field data from sites with different conditions will also

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[121] As mentioned in earlier chapter on LCA, the use of different functional- and energy-units makes comparative LCA studies difficult.

[122] The GREET 1.6 and the GHGenius (www.ghgenius.ca) are examples of models used for lifecycle analysis of fuels.

improve the 'generalizability' and 'transferability' of the results of LCA studies. Accurate results from LCA studies cannot be obtained without data and statistics from field studies. Therefore, correct and reproducible data from field studies[123] are necessary to make reliable assessment about the sustainability of biofuels.

Besides the GHG and energy balance in the LCA studies, there are considerable uncertainties in the water footprint of biodiesels, especially in the case of jatropha, due to the lack of data regarding the water usage in the agricultural stage of biofuel production. The use of biomass-based water use efficiency (WUE) is suggested as a possible 'unifying' unit to express the water usage of jatropha and other biofuel feedstock. The variability in the WUE for a specific plant with environmental conditions may prove to be useful in converting the WUE data from one site to predict the values in other sites. As mentioned in the earlier chapter *'The water footprint of jatropha'*, the development of empirical equations and models and the use of appropriate indices are recommended for accurate prediction of water usage using WUE. Moreover, sustainable irrigation practices must be adopted to cater to the water requirements of the biofuel feedstock under consideration. At the same time, any competition for water resources with food crops must be avoided. The use of wastewater treatment plant effluent is suggested to minimize the freshwater consumption.

In the context of biofuels, another area of ambiguity is the improper use of terminology. For example, 'biodiesel' refers to the finished product of the

[123] The dearth of field data for yields and water consumption is especially true for jatropha.

transesterification of vegetable oils that adheres to ASTM standards. There are standard tests and regulations that finished products should meet in order to be categorized as 'biodiesel'. As these standard procedures use specific raw materials, catalysts and reaction conditions, the methods for biodiesel manufacture and the finished products are expected to be similar for industrial and laboratory scale procedures. However, in conducting this literature review on biodiesels, it was observed that the term 'biodiesel' was used to refer to the end products of transesterification, without examining if the product adhered to ASTM regulations for emissions or engine performance. This becomes important when estimating the "GHG emissions per mile" for the 'biodiesel' as the engine performance plays a significant role in this estimation. It is therefore hard to compare and contrast the performance of such 'biodiesels'[124]. It is understood that many laboratories may not have the necessary facilities to produce biodiesels that match all the ASTM criteria. It is suggested that a subcategory of biodiesel be created with a minimum set of predefined physical and chemical properties. Transesterification end products must meet this minimum set of criteria for the experimental results to qualify as a study on biofuels. This will ensure more homogeneity in the studies.

Biotechnological advancements are the key to improving the yield, the WUE, the GHG performance and the energy balance of energy crops. Besides improving

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[124] In a letter to the editor of 'Fuel', Lois (2007) has emphasized on the need to define a set of properties that the 'finished product' must adhere to, in order to qualify as 'biodiesel'. However, the author also warns that if the definition is too strict, many experimental results might not result in publications. The author has mentioned: "What is needed in my view is a minimum set of properties that characterize pure biodiesel, before a paper is acceptable for publication."

the aforementioned properties, in the case of jatropha, further research on the genetic modification is recommended for improving the oil content and combining non-toxic varieties with the high yielding toxic species to obtain seedcake with significantly lower level of toxins[125]. Further research on the genetic modifications must aim to improve the drought tolerance of energy crops that can produce high yields in marginal lands with low soil nutrient content. The possibility of 'inherently carbon negative' energy crops must also be explored. By 'inherently carbon negative' energy crops, I am referring to the possibility of improving the GHG balance to such an extent that the net CO_2 balance is negative, in spite of the use of fertilizers and other agrochemicals. This is different from the carbon negative biofuels discussed by Tilman et al. (2006). Tilman et al. (2006) studied perennial grassland species grown on degraded soils without irrigation or the use of agrochemicals. The authors found the carbon balance to be negative, primarily because of the low inputs involved.
By 'inherently carbon negative' energy crops, I am suggesting that the carbon balance be improved and made negative by biotechnological changes in the plant, and not by any changes in the agricultural practices.

Besides the members of the scientific community, the policymakers also have a significant role to play in shaping the future of biofuels. The state and national policies must promote sustainable biofuel programmes, and at the same time,

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125 Gressel (2008) mentioned that the seed cake of jatropha currently has negative economic value due to the presence of several toxins and has suggested that the phorbol esters content be suppressed by genetic modifications. The author also suggested other genetic modifications to reduce the height of full-grown jatropha plant, decrease branching and incorporate 'anti-shatter' genes to form 'shatterproof' seeds to help in mechanizing the harvesting process.

protect the rights of the local population. International policies must ensure that the budding economies in the developing world are adequately protected from future changes in biofuel-related policies in the industrialized nations.

It is vital to improve the existing biofuel technologies using an integrated, multidisciplinary approach involving areas of genetics, plant breeding and molecular biology. Simultaneously, national and international authorities must revise biofuel policies to promote non-food based biofuels. The existing uncertainties in the sustainability studies must be addressed by generating reliable field data and using improved LCA techniques. Biofuel programmes must also aim to increase public awareness to clarify any misconceptions related to biofuels, while making the information regarding novel technological advancements available. These steps would go a long way in ensuring that the potential environmental and societal benefits of biofuels are utilized.

Conclusions:

With an increasing world population and improving living standards, there are increasing demands for food as well as fuel. Major improvements in both the agricultural practices and biofuel technologies are essential to meet these twin, and at times, antagonistic demands. Food-based biofuels (e.g., ethanol from corn) aggravate food insecurities and exacerbate world hunger. Non-food-based, second generation biofuels offer an alternative that does not compete with food. However, the technologies and the capacity for the large-scale production of second-generation biofuels (e.g., from switchgrass and algae) are still years away. As the growth of plant biomass is strongly dependent on environmental conditions, perhaps it is time to reevaluate if the search for the 'wonder-crop', that one perfect biofuel feedstock is a mirage. Perhaps it is best to choose the feedstock in any particular region based on the climatic conditions, the available resources and infrastructure. While second-generation biofuel technologies are pursued in the industrialized nations, the developing nations with favourable climates can produce biofuels from first-generation, non-food feedstock such as jatropha, to gradually wean the world from food-based biofuels.

Biofuels from non-food feedstock (e.g., jatropha) may also compete with food for resources (e.g., land, water and labour). Therefore, the proper management of these resources is essential to avoid any worsening of the agricultural impacts of biofuels, to prevent negative environmental impacts (e.g., loss of habitat and biodiversity) and to safeguard against unsustainable agricultural and irrigation practices. The concerns regarding the sustainability of biofuels are integrally linked to the findings in their LCA studies. While jatropha holds promise as a biofuel feedstock, its sustainability is still questionable because of the lack of established best practices in the agricultural and the biodiesel-production stages as well as the uncertainties in the LCA studies. Besides the GHG balance, a major area of uncertainty is the water footprint of jatropha. The sustainability of biofuels depends on the feedstock as well as the scale of production. Therefore, until further studies are conducted to validate jatropha's sustainability on a larger scale, it would be beneficial to promote jatropha at the community level to help the rural population in the developing nations benefit from this multipurpose plant and meet their energy demands.

The issues of the sustainability of biofuels, escalating food prices and the so called 'energy crisis' are intertwined; three aspects of the problem must be clearly understood. First, there are genuine concerns about the depleting reserves of fossil fuels and therefore there is a growing need for alternative, renewable and sustainable energy sources. Secondly, as revealed by the food-biofuel conflict, there is pressing need for promoting sustainable agricultural practices with significantly improved production efficiencies. Lastly, it is essential to educate consumers about the issues of sustainability while simultaneously inculcating responsible consumption habits. These three areas of concern must be addressed simultaneously for the future energy-related endeavours to be successful.

Appendix:

Detoxification of Phorbol Esters in Jatropha Seeds using Ozone:

Materials and Methods:

Seed samples of *Jatropha curcas* from Mali (Biocarburant Jatropha Extraction Plant, Kulikoro, Mali), Florida (University of Florida, Gainesville, Florida) and India (M/s Gautam Global, Dehradun, India) were used for the initial detoxification experiments. The seeds were ground (without removing the shells) in a coffee grinder (Braun KMM 30 Coffee/Expresso Mill, Model 3045). 20 g of ground seeds was extracted with 150 mL of methanol (99.99% purity, HPLC grade, Sigma Aldrich) for 16 hours using a Soxhlet extractor.

The extract was allowed to settle in a fume hood and the solvent (methanol) was allowed to evaporate under room temperature until the resulting volume was approximately 50 mL. The concentrated extract was decanted and cold-centrifuged (4±2 °C, set point: 4°C) at 20000 rpm for 60 minutes. The extract was then filtered through 0.45 μm membrane filter (Millipore, catalog number HAWP02500, filter material: mixed cellulose esters) and diluted with methanol before analyzing in HPLC (Waters, with Waters 2487 Dual λ Absorbance Detector). The method for HPLC analysis was based on those used by Makkar et al. (1997) and Haas and Mittelbach (2000) with some modifications.

HPLC conditions:

An isocratic solution of 80% acetonitrile[126] and 20% HPLC grade water[127] (with 1.75 mL orthophosphoric acid[128] per litre of water) was used, keeping a constant flow rate of 1 mL min^{-1}. In the initial stages of the project, a 150 mm × 4.6 mm, C-18, end-capped 5 μm (Supelco) HPLC column was used. Later, this was replaced with a 250 mm × 4.6 mm, Lichrospher C-18, end-capped 5 μm (Supelco) for better separation. Phorbol-12-myristate-13-acetate (PMA) (Sigma Aldrich, product number P8139) was used as the standard for phorbol esters.

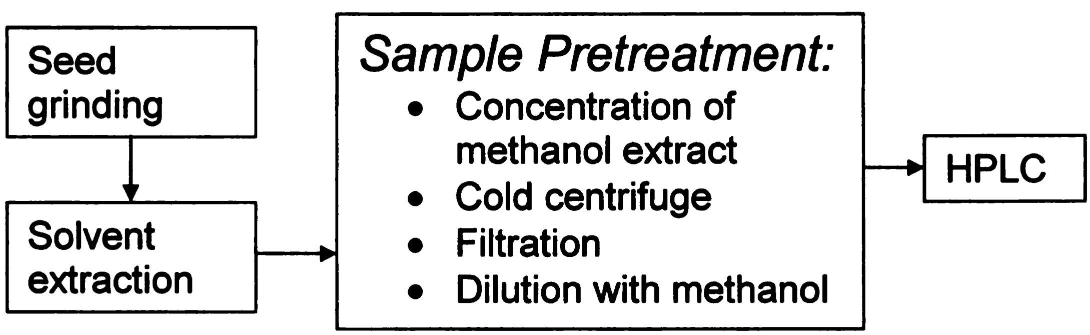

Figure 2 - Schematic of experimental procedure

Sampling in HPLC:

The isocratic solution was run at 1 mL min^{-1} for 30 minutes to achieve stable conditions in the column. After setting the UV wavelength at 235 nm[129],

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126 solvent A, 99.93%, HPLC grade, Sigma Aldrich, product number 34851

127 solvent B, J.T. Baker, product number 4218-03

128 85%, Fluka, product number 79617

129 All conditions remaining equal, the peak area for the PMA standard was significantly higher for UV wavelengths in the range of 230 - 240 nm than at 280 nm. So, all the HPLC analyses were done with a UV wavelength of 235 nm. (Almost all the methods referred to in the literature used 280 nm as the UV

methanol was injected into the HPLC system. All injection volumes were 20 µL. Once a stable baseline was obtained the PMA standard was injected. The residence time for the PMA standard was about 22 minutes for the 15 cm column and 41 minutes for the 25 cm column. A calibration curve was prepared using different concentration of the PMA standard. Using the peak areas from the extract, the phorbol esters' concentration was calculated from the calibration curve (as PMA equivalent)[130].

200 µL of the jatropha seed extract was added to 1 mL of methanol and injected into the HPLC system. The sample run time was set for 55 minutes. Before the next sample injection, a gradient elution from 80% to 100% acetonitrile (with a 2.5% increase every 2 minutes) was used to flush out the residual hydrophobic components in the column. The ratio of 100% acetonitrile and 0% water was maintained for 10 more minutes. To prepare for the next run for the extract, the ratio of the solvents was restored to 80% acetonitrile and 20% water (with a 2.5% decrease every 2 minutes) to restore the isocratic conditions. The total runtime was 97 minutes (55 min + 16 min + 10 min 16 min).

Ozonation:

One milliliter of the jatropha seed extract was diluted with 5 mL of methanol and ozonated in a 10 mL vial using a ceramic diffuser connected to a glass tube. The

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wavelength for HPLC analysis. Vogg et al. (1999) have used 220 nm wavelength for the UV detector in HPLC prior to mass spectroscopic analysis of diterpene esters.)

[130] The calibration curve and the related calculations are presented in the Appendix.

ozone generator (Ozotech) was run at the setting ‘8’. The gas flow rate (oxygen + ozone) was maintained at 1 L min^{-1} using a rotameter. The concentration of ozone at the inlet was monitored with a digital ozone monitor (Teledyne Instruments Model 454H). The residual ozone concentration could not be checked, as a second ozone monitor was not available. The reading in the ozone monitor fluctuated between 21 – 26 g m^{-3}. Samples were ozonated for 2, 5, and 10 minutes and then analysed in HPLC[131].

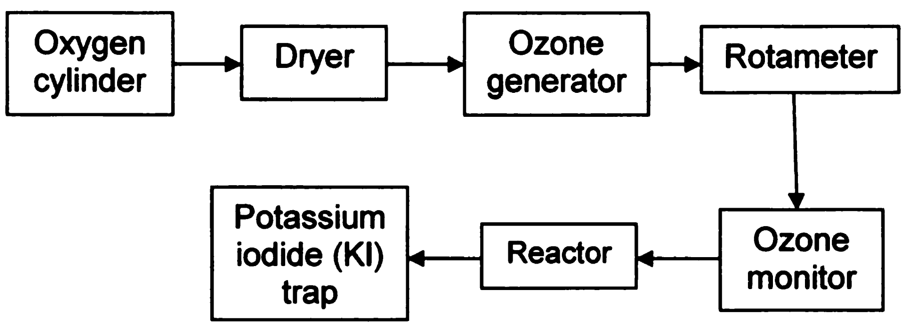

Figure 3 - Schematic of ozonation setup

Results:

Detoxification of jatropha seedcake would increase its value as a byproduct as it may then be used as animal fodder. Ozonation was tried as a means of detoxification. As fresh seedcake samples were not available, the detoxification experiments were carried out using liquid extracts from the seeds. The first batches of seed samples were obtained from Mali, Florida and India. A second

[131] The concentrations of phorbol esters (as PMA equivalent) before and after ozonation are presented in the Appendix.

batch of seeds and seedcake was obtained from Mali. It was found that the peaks for phorbol esters were not present in the older seed samples from Mali, Florida and India. All the data and calculations presented are based on the analysis of the second batch of samples from Mali.

The following results were found from the peak areas[132] of the chromatograms from HPLC:

a) Phorbol esters concentration in the jatropha seeds from Mali: **0.14 $mg \cdot g^{-1}$ of seed** (expressed as PMA equivalent).

b) An applied dose of **0.10 g** of ozone was reduced the phorbol esters content by **72.6%**.

[132] Calculations of concentrations from peak areas are presented in the Appendix.

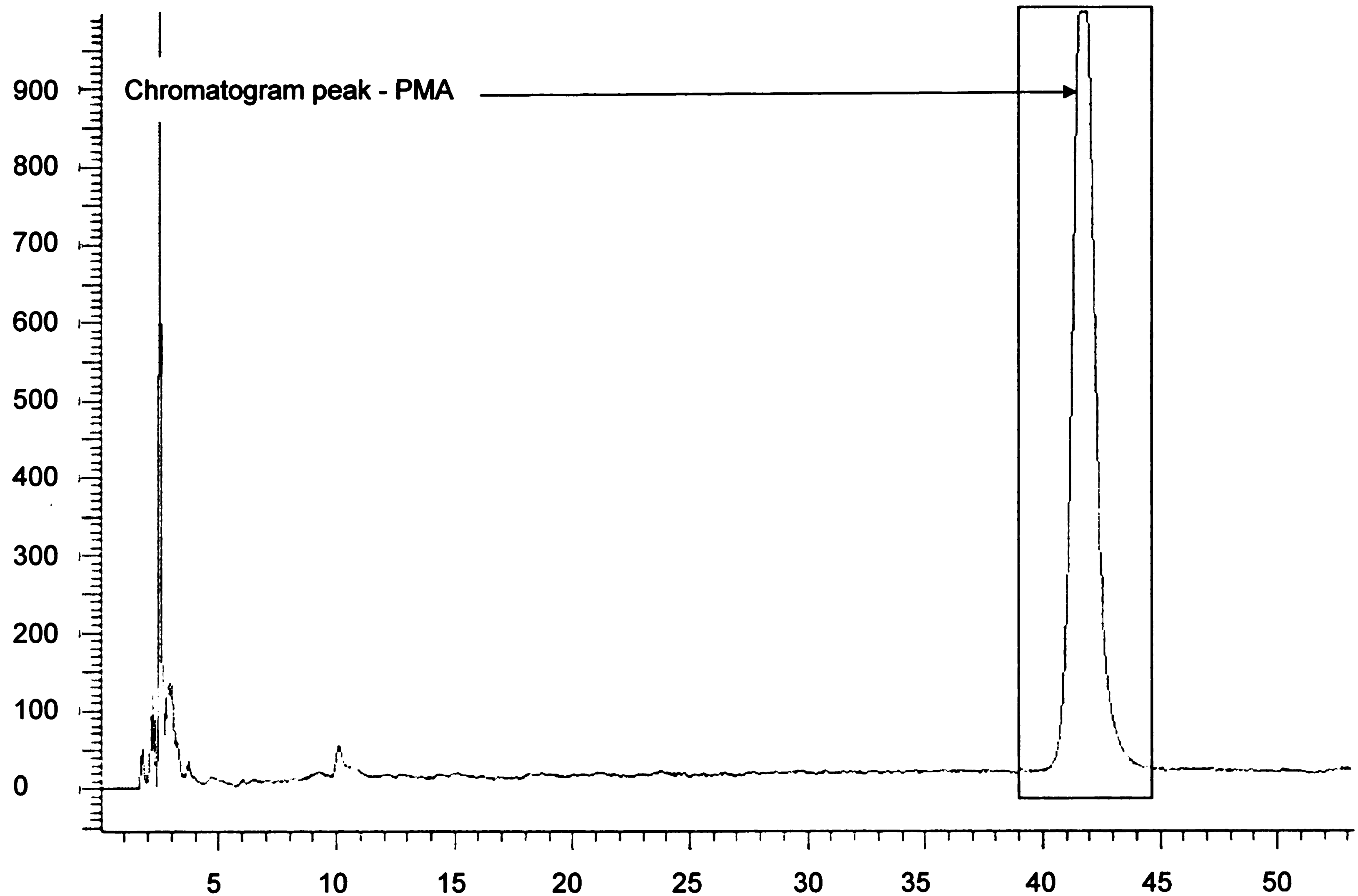

Figure 4 - Chromatogram of PMA standard

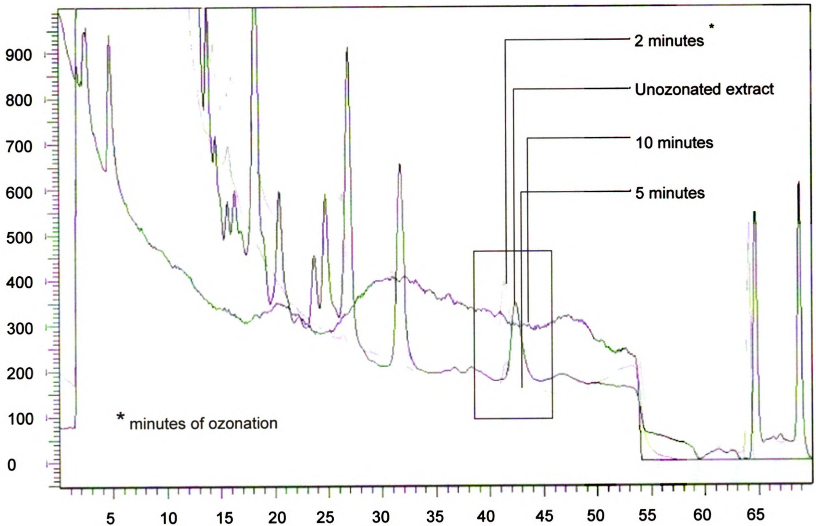

Figure 5 - Chromatogram of ozonated and unozonated jatropha seed extracts

Discussion:

Phorbol esters concentrations in jatropha have been reported to be 2 - 5 $mg \cdot g^{-1}$ of seeds (Makkar et al. 2008) and 0.87 - 3.32 $mg \cdot g^{-1}$ of kernel (Makkar et al. 1997). Compared to these values, the concentration of phorbol esters found in the seeds from Mali is much lower. (The concentration in non-toxic varieties is reported to vary from non-detect levels to 0.11 $mg \cdot g^{-1}$ of seeds (Makkar, Aderibigbe and Becker 1998).) It is believed that the low value of phorbol esters' concentration is due to the fact that the seeds were not fresh and there might have been some degradation during the transportation and storage of the seeds.

In the experiments, PMA was the only standard used for detecting phorbol esters and the concentrations were expressed as PMA equivalent. Phorbol esters other than PMA were not considered in the calculations. Moreover, based on the literature review, peaks corresponding to other phorbol esters were not observed close to the peaks for the PMA standard. As more than one variety of phorbol esters are known to be present in jatropha seeds (Haas, Sterk and Mittelbach 2002), it is recommended that more than one standard for phorbol esters be used for more accurate quantification. Phorbol-13-acetate, phorbol-12,13-diacetate, phorbol-12,13,20-triacetate, phorbol-12-N-methylanthranilate-13-acetate, phorbol-12-deoxy-13-tetradecanoate are some of the standards used in HPLC analyses of diterpene esters (Vogg et al. 1999).

Although the phorbol esters concentration was reduced by ozonation, further research in this area is recommended to identify the ozonation byproducts and assess their toxicities.

The stoichiometry of the reaction between ozone and phorbol esters was not studied. Therefore the relation between ozone dose and the decrease in phorbol esters concentration may not be linear (as assumed in the calculations for ozone dose). A liquid sample (jatropha seed extract) was ozonated in all the experiments conducted so far. However, the ozone dosage required for the actual seedcake could be significantly different (expected to be more), as that would involve ozonating the solid seedcake. Also, one must bear in mind that the ozone dose mentioned in the calculations was the applied dose and not the absorbed dose.

Ozonation is an expensive process. Most jatropha plantations and (therefore detoxification facilities) would be located in the tropical belts, especially in developing world. Therefore, low cost solar ozonators are a prerequisite for such facilities to function, as the operating costs for conventional ozonation facilities would be too high[133].

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[133] Potivejkul et al. (1998) described the detailed design of solar powered ozone generator.

Raw Data:

Table 1 - PMA calibration (Raw data -1)

Area of the peak (uV-sec)	PMA concentration (mgL^{-1})
3.87E+05	1
3.33E+05	1
3.11E+06	5
3.70E+06	5
4.02E+06	5
9.75E+06	10
8.67E+06	10
1.00E+07	10
2.36E+07	25
2.08E+07	25
2.11E+07	25
4.77E+07	50
4.69E+07	50
5.32E+07	50

Table 2 - PMA calibration (Raw data -2)

Average area of the peak (uV-sec)	PMA concentration (mgL^{-1})
3.60E+05	1
3.61E+06	5
9.49E+06	10
2.18E+07	25
4.92E+07	50

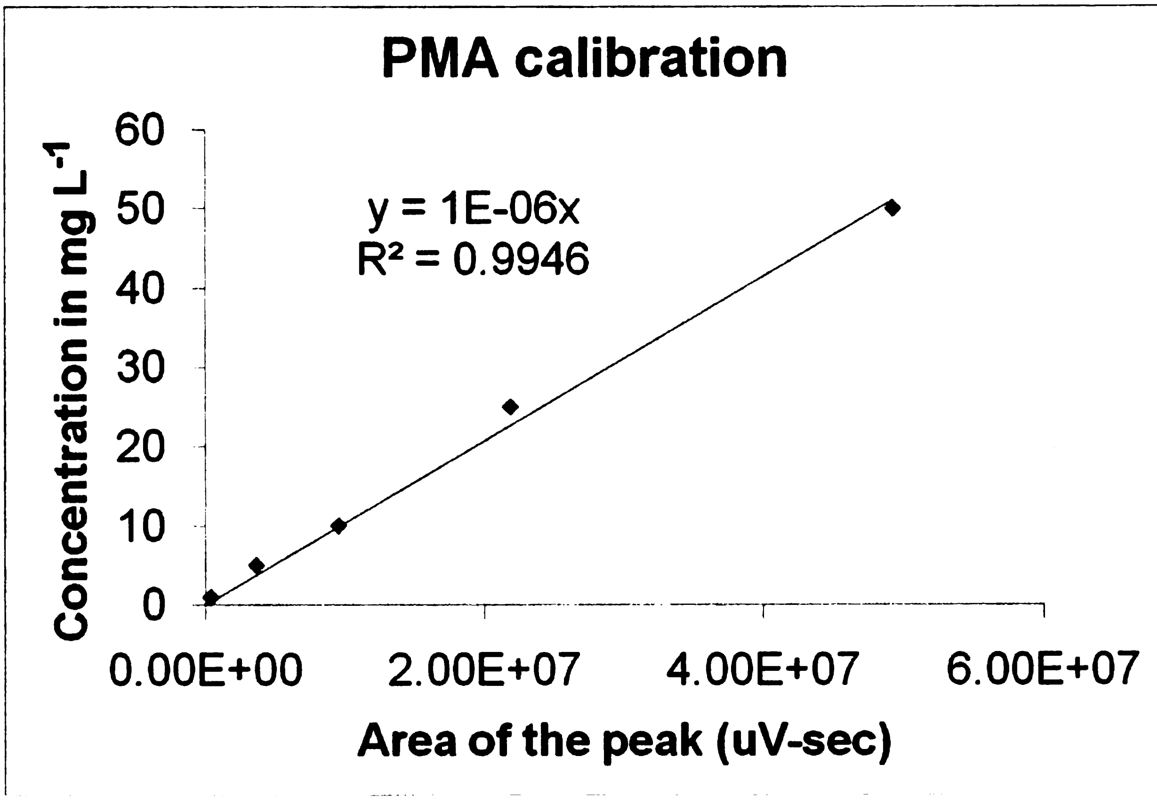

Figure 6 - PMA calibration curve

Table 3 - Ozonation (Raw data)

Sample	Average area of the peak (uV-sec)	PMA concentration (mgL^{-1})
Unozonated extract:	9.47E+06	9.47
After 2 min of ozonation	7.95E+06	7.95
After 5 min of ozonation	2.60E+06	2.60

Percentage reduction in concentration after 5 minutes of ozonation

= (9.47 mgL^{-1} - 2.60 mgL^{-1})/(9.47 mgL^{-1}) * 100%

= 72.6%

Table 4 - Applied ozone dose

Average flow rate of ozone	21 g m^{-3}
Gas flow rate (ozone + oxygen)	1 L min^{-1} = 0.001 m^3 min^{-1}
Flow rate of ozone in g min^{-1}	0.02 g min^{-1}
Applied ozone dose in 5 minutes	0.10 g

Therefore, an applied ozone dose of **0.10 g** was required to achieve a **72.6%** reduction in the phorbol esters' content.

Calculations:

Phorbol esters content in the jatropha seeds (shell + kernel):

1 mL of extract was diluted with 5 mL methanol before ozonation.

Therefore, the dilution factor = 6

As seen from the previous data of the peak areas in the chromatogram, the phorbol esters' concentration in the jatropha seed extract after dilution is 9.47 mgL^{-1}

Therefore the concentration of phorbol esters in the seed extract before dilution

= 6 * 9.47 mgL^{-1}

= 56.84 mgL^{-1}

Let the weight of PMA in 50 mL of the extract be x mg.

Therefore,

$(x\ mg/50\ mL)*(1000mL/L) = 56.84\ mgL^{-1}$

Or **x = 2.84 mg**

Therefore 20 g of ground jatropha seeds contain 2.84 mg of phorbol esters (as PMA equivalent)

Thus, the concentration of phorbol esters in the jatropha seeds is

0.14 mg g^{-1} of seeds.[134]

134 Shell + kernel

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