

# Jatropha Biofuels

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## Miracle Plant or Economic Hazard?

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December 9, 2009

E555 Energy & the Environment  
School of Public & Environmental Affairs  
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## Introduction to Jatropha

### Recent Interest

Over the past three years, a shrubby tree called jatropha has landed in the headlines of major news outlets, from *The Wall Street Journal* to *Time* magazine to *The New York Times* (Barta 2007, Browne 2009, Dubner 2007, and Padgett 2009). Its claim to fame: oil. Jatropha produces oily seeds that have been hailed as a potential alternative to petroleum diesel. Rising concerns about global climate change, peak oil, and energy security have helped push jatropha into the spotlight. However, the use of jatropha as a diesel alternative is hardly a new concept—during World War II, jatropha oil was used in place of fossil diesel in Madagascar, Cape Verde, and Benin (Agarwal 2007). Today, though, the motivation has changed. Developing nations have seized on jatropha as a tool for both expanding their energy infrastructure and developing their economies, all the while avoiding the pollution of fossil fuels. Yet, as with most biofuels, researchers must still determine whether jatropha is a miracle plant that can drive sustainable development in some of the poorest regions of the world or an economic hazard that could ruin peasant farmers and run rampant over fragile ecosystems.

### Botanical Information

Jatropha, a member of the Euphorbiaceae family, is native to the American tropics but has been transported to many tropical and sub-tropical regions of Africa and Asia (Augustus et al. 2002 and Openshaw 2000). This exchange occurred early in the period of European colonization, with Portuguese sailors most likely bringing the plant to Africa and Asia by means of the Cape Verde islands and Guinea Bissau (Gubitz et al. 1999). The name “jatropha” generally refers to the species *Jatropha curcus*, also called physic nut (Kandpal and Madan 1995). Jatropha is characterized as a drought-resistant shrub with large leaves, which it sheds in the dry season (Augustus et al. 2002 and Gubitz 1999). It achieves a height of three to four meters within its first three years, a maximum height of about five meters, and a maximum age of about 50 years (Augustus et al. 2002 and Openshaw 2000). It generally flowers two times per year, with each fruit bearing two to three seeds (Kandpal and Madan 1995). Although certain Mexican varieties are reported to be non-toxic to animals and humans, most jatropha varieties

cause nausea, gastro-intestinal irritation, abdominal pain, vomiting, diarrhea, and dehydration when ingested due to the presence of phorbol esters in the plant (Gubitz 1999).

#### **Claimed Positive Attributes**

Jatropha is credited with a long list of positive attributes, many of which are still under investigation or subject to qualifications. For example, jatropha is widely confirmed to be a drought-resistant tree, but jatropha fruit production declines under dry conditions since the tree loses its leaves to conserve resources during stressful events (Prueksakorn and Gheewala 2008 and Openshaw 2000). Similarly, although jatropha is capable of growing on marginal lands with few nutrient inputs, fruit yields generally suffer under such conditions (Openshaw 2000). Nonetheless, jatropha's hardiness and rapid growth make it a prime candidate for erosion control and land reclamation (Openshaw 2000). In addition, the plant is often used as a living fence around fields since most varieties are toxic to animals and the tree grows quickly from cuttings (Gubitz et al. 1999).

Jatropha is touted as an insect-resistant plant. Parts of the tree have even been used as an insecticide against the corn weevil, the bean weevil, the common housefly, the cotton bollworm, and the cotton flowerweevil (Gubitz et al. 1999). Some studies have found that jatropha oil is superior to synthetic insecticides because it does not harm beneficial insects (Gubitz et al. 1999). However, jatropha is not immune to all pests. Researchers in Nicaragua have found a jatropha fruit loss of up to 18.5 percent due to two common insects, *Pachycoris klugii* and *Leptoglossus zonatus* (Gubitz et al. 1999). The effects of other pests, such as fungi, on jatropha have not yet been carefully studied, although the tree seems resistant to most pests (Openshaw 2000).

Finally, jatropha is claimed to have many medicinal applications, including the following: use as a purgative, treatment of skin diseases, relief of rheumatism pains, soothing of coughs, healing of wounds, reduction of inflammation, treatment of malaria, use as a contraceptive, and inducement of abortion (Gubitz et al. 1999). Only a few of these applications have been carefully studied. One example is the anti-inflammatory properties of jatropha, which have been traced to a substance in the leaves (Gubitz et al. 1999).

#### **Use as a Biofuel**

##### **Planting Requirements**

When growing jatropha as a biofuel feedstock, the primary goal is to maximize oil production, which is accomplished by maximizing both seed yield per hectare and oil yield per

seed. The appropriate crop density varies widely, depending on regional factors such as climate and soil characteristics, but is usually between 1100 and 3300 trees per hectare (Prueksakorn and Gheewala 2008). A general spacing guide for jatropha planted in fields is 2-3 meters by 1.5-3 meters, while trees planted in hedges should be spaced at 15-25 centimeters (Openshaw 2000). Although some studies suggest that greater spacing results in greater productivity, more research is needed to confirm this (Openshaw 2000). In the first year of each growing cycle, the land must be prepared, although the amount of land modification will depend on the previous land use, soil properties, and equipment availability. Average diesel consumption for field preparation is 25 to 40 liters per hectare (Prueksakorn and Gheewala 2008). Most studies recommend propagation by seed rather than by cutting because it encourages the formation of a taproot in addition to lateral roots (Achten et al. 2007, Prueksakorn and Gheewala 2008). Trees propagated by cutting can help control sheet erosion due to their dense lateral roots, but they will not survive extreme weather events, such as high winds and landslides (Achten et al. 2007).

#### **Tending Requirements**

Once the trees are planted, they require 900 to 1200 millimeters of yearly rainfall (Prueksakorn and Gheewala 2008). Jatropha can be strategically planted near the start of the rainy period to ensure proper watering during the initial stages of plant growth (Openshaw 2000). In the absence of sufficient rain, the trees can survive but will yield fruit for only one period per year (Prueksakorn and Gheewala 2008). With irrigation, the trees can yield fruit up to three times per year (Openshaw 2000). The amount of energy expended to irrigate will depend on both the local climate and the chosen irrigation method—diesel pumps, siphoning, drip irrigation, or manual labor (Prueksakorn and Gheewala 2008). Similarly, fertilization requirements are highly tied to local land characteristics, but some amount of fertilization is generally necessary since low nutrient levels can cause seed failure (Openshaw 2000). Chemical fertilizers or animal manure can supply essential nutrients, such as nitrogen (Openshaw 2000). A more cost-effective solution for small jatropha growers may be to cultivate jatropha alongside nitrogen-fixing plants (Openshaw 2000). Starting in the second year of the growing cycle, jatropha seedcake can be substituted for chemical fertilizers, with 1.0 kg of seedcake replacing 0.15 kg of N:P:K (40:20:10) chemical fertilizer (Prueksakorn and Gheewala 2008).

Pests can often be handled without chemical methods. For example, given the toxic nature of most jatropha varieties, grazing animals can be released into jatropha fields where they

will browse weeds without harming the trees (Prueksakorn and Gheewala 2008). Furthermore, insecticides are generally avoided on jatropha fields because they can harm pollinators, which are essential to fruit productivity (Prueksakorn and Gheewala 2008). Finally, as noted above, many pests do not attack jatropha since the tree itself has insecticidal properties.

#### **Trimming and Thinning Practices**

Once plantations are established and proper tending practices are implemented, large-scale management practices, including trimming and thinning of trees, must be addressed. Hedges must be trimmed to maintain order and decrease competition, while fields must be thinned as the trees mature (Openshaw 2000). Trees can be planted at high density the first year to encourage a harvestable crop and then thinned by as much as 75 percent the second year to prevent photosynthetic interference and nutrient competition (Prueksakorn and Gheewala 2008). In that case, the wood from the thinned trees can be used for other purposes, such as firewood or fencing (Prueksakorn and Gheewala 2008). Finally, trees must be regularly pruned to encourage high density of fruiting (Openshaw 2000).

#### **Expected Harvests**

Data regarding jatropha yields are highly variable, and caution must be exercised when evaluating claims since many growers advertise inflated yields in order to sell their seeds to new growers. However, a detailed study of jatropha plantations in Thailand offers a sample of jatropha seed yields based on worst and best cases. The study reports a yield of 0-5,000 kilograms of seed in the first year, 350-12,500 kilograms of seed in the second year, and 880-12,500 kilograms of seed in the third year (Prueksakorn and Gheewala 2008). The study found maximum productivity can be reached in 2-3 years at the earliest and maximum productivity can be sustained for 20 years (Prueksakorn and Gheewala 2008). In the best case, the average biodiesel yield is 2.7 tons per hectare per year, which is comparable to the results reported by D1 Oils, one of the foremost jatropha biodiesel companies in the world (Prueksakorn and Gheewala 2008).

Another study based in India found jatropha yields of 4-5 kilograms of seed per tree by the fifth year after plantation, which equates to 4,000 to 15,000 kilograms per hectare at 1,000 to 3,000 trees per hectare (Singh et al. 2008). The same study found the trees can remain productive for 40 to 50 years after plantation but cautioned that seed yields fall to 1-1.25 kilograms per tree in nutrient-poor or water-restricted conditions (Singh et al. 2008).

### **Processing Requirements**

Jatropha seeds are approximately 30 to 40 percent oil by weight (Agarwal and Agarwal 2007). In order to produce biodiesel, the oil must be extracted from the seeds. Two methods currently exist to extract the oil: solvent extraction and mechanical extraction. Solvent extraction yields 70 to 99 percent of the available oil, but this method is energy intensive and too expensive for the current scale of production (Achten et al. 2007). Therefore, most producers use mechanical extraction, which yields 60 to 80 percent of the available oil (Achten et al. 2007).

Raw jatropha oil is considerably more viscous than petroleum diesel (Singh et al. 2008). Therefore, once the oil is extracted, it must be de-waxed and de-gummed to make it suitable for use in compression ignition engines (Singh et al. 2008). The jatropha oil is then usually converted to biodiesel via transesterification in order to reduce the viscosity of the oil (Agarwal and Agarwal 2007). During transesterification, the oil is combined with alcohol (methanol or ethanol) and a strong base catalyst (potassium hydroxide or sodium hydroxide) in a heating tank (Prueksakorn and Gheewala 2008 and Singh et al. 2008). In one Thai study, electricity consumption for the transesterification process was measured at 3.8-4.1 kWh per batch with 80 L of oil processed per batch (Prueksakorn and Gheewala 2008). The resulting products are methyl esters (biodiesel) and glycerin in a ratio of about 78 percent biodiesel to 22 percent glycerin (Prueksakorn and Gheewala 2008 and Singh et al. 2008). Transesterification can attain efficiencies of 95.0-97.5 percent by weight (Prueksakorn and Gheewala 2008). Although engines can be modified to run on pure vegetable oil, most biofuel producers find it simpler to convert vegetable oil into biodiesel than to modify existing engines (Gubitza 1999).

### **Suitability as a Fuel**

Although the calorific value of jatropha oil and petroleum diesel are fairly comparable (9,470 and 10,170, respectively), the use of pure jatropha oil in unmodified diesel engines is generally not recommended because the high viscosity and high flash point of jatropha oil can cause engine problems, including ignition failure and incomplete combustion (Agarwal and Agarwal 2007, Kandpal and Madan 1995, and Openshaw 2000). Nonetheless, researchers have found that pure jatropha oil that has been de-waxed and de-gummed (but has not been converted to biodiesel) can be run in unmodified diesel engines in blends of up to 20 percent jatropha oil and 80 percent petroleum diesel (Singh et al. 2008). The jatropha oil content can be increased to as high as 50 percent if the fuel blend is preheated to reduce its viscosity (Singh et al. 2008). At

about 100 degrees Celsius, the viscosity of jatropha oil approaches that of petroleum diesel (Agarwal and Agarwal 2007).

However, caution is merited because as the jatropha oil content of the fuel increases, the brake thermal efficiency of the engine decreases due to the lower energy content of jatropha oil (Agarwal and Agarwal 2007 and Singh et al. 2008). At blends above 50 percent jatropha oil, the engine is unable to burn all of the oil particles and produces large amounts of white smoke (Singh et al. 2008). Furthermore, long-term tests of vegetable oil fuels have indicated reduced engine performance due to gum formation, carbon deposits in the combustion chamber, piston ring sticking, and injector coking (Agarwal and Agarwal 2007). In contrast to jatropha oil blends, jatropha biodiesel blends result in greater brake thermal efficiency and lower specific energy consumption than pure petroleum diesel (Singh et al. 2008). This is due to the oxygen content in jatropha biodiesel, which promotes efficient combustion, and to the slightly higher viscosity of jatropha biodiesel, which helps lubricate the engine (Singh et al. 2008).

#### **Energy Balance**

The energy balance of jatropha biodiesel can be found through a life cycle study, in which the energy inputs and outputs over the entire lifespan of the fuel are calculated. One such study was completed by Prueksakorn and Gheewala in 2008 with a focus on the Thai biodiesel industry. The study considered the energy balance of jatropha biodiesel and its primary co-products—seedcake, glycerin, wood, and peel—based on a 1-hectare jatropha plantation over a period of 20 years. The study considered the following production stages: jatropha cultivation, oil extraction, biodiesel production, and transportation throughout the other processes. The study did not consider the energy necessary to construct buildings, manufacture equipment, or fuel manual labor. The researchers found net energy ratios between 1.93 and 11.99, with an average of 6.03, for the scenarios in which all of the co-products were considered (see Table One in the Appendix). When biodiesel alone was considered, the net energy ratio ranged from 0.53 to 2.70, with an average of 1.42. Overall, the average net energy gain was 4,720 gigajoules per hectare when all co-products were included (Prueksakorn and Gheewala 2008).

The study found that the average energy consumption was highest during the cultivation stage and lowest during the oil refining stage. Jatropha cultivation on infertile land required twice the energy of cultivation on fertile land because of increased fertilization and irrigation. In fact, fertilizer production represented 30 percent of the overall energy consumption, while

irrigation represented 13 percent of the total. Therefore, energy consumption could be greatly reduced through the substitution of organic fertilizers for chemical fertilizers and the use of low-energy irrigation systems. Transportation was the most uncertain aspect of the analysis, ranging from 7 to 648 gigajoules. This is because transportation distances and methods varied widely depending on the location of the plantation, the refinery, and the marketplace, as well as the sourcing location of primary materials. The final estimates were based on a series of distance assumptions combined with measured diesel consumption rates for pick-up trucks, 10-wheel trucks, and ships. Careful planning that promotes local collaboration can greatly reduce the energy consumption from transportation and therefore increase the net energy gain (Prueksakorn and Gheewala 2008).

The total energy output for all considered co-products ranged from 2,534 to 8,784 gigajoules per hectare. The use of seedcake as fuel yielded the highest energy return. For comparison, the avoided energy consumption from the use of seedcake fertilizer in place of chemical fertilizer equaled only one third of the energy output gained from the burning of the seedcake. However, other considerations—such as the atmospheric emissions from seedcake combustion, the ecological effects of chemical fertilizers, and the economic tradeoffs—must also be considered when deciding the best use of the seedcake (Prueksakorn and Gheewala 2008).

## **Economics: Costs and Revenues**

### **Cultivation and Harvesting Costs**

As with any agricultural crop, the cost of jatropha cultivation differs between geographic regions due to variability in soil and climate conditions. Openshaw (2000) provides a rough outline of these costs based on an Indian study (see Table Two in the Appendix). The total cost of establishment and tending for the first six years is \$343 per hectare. At \$255, fertilizer costs make up nearly 75 percent of this total. Labor constitutes the second greatest share at \$76, while plough hire and seeds demand only \$9 and \$3, respectively. A more detailed table of costs (see Table Three in the Appendix) reveals that seedcake was applied in place of chemical fertilizer, beginning in year two. The cost of the seedcake is a combination of manufacturing, transport, handling, and spreading expenses. However, a yearly increase in the quantity of seedcake applied to the field is not explained by the author (Openshaw 2000).

The same paper offers a summary of harvesting costs (see Table Four in the Appendix). The total cost for the first six years is \$107 per hectare based on a fruit yield of 16.75 dry tonnes

per hectare. This cost is roughly distributed into thirds between collection, de-coating, and shelling (\$38, \$38, and \$31, respectively). If 4.0 dry tonnes of wood are also collected as a result of trimming and thinning trees, then the harvesting cost rises to \$127 per hectare, primarily due to increased labor costs (Openshaw 2000).

#### **Processing Costs**

Openshaw (2000) also evaluated the processing costs of jatropha biodiesel based on factories in India and Zimbabwe. The results indicate that jatropha biodiesel production is not cost competitive with petroleum diesel. The study found a cost of 65.45 to 72.89 cents per liter for jatropha biodiesel, compared to a cost of 16.57 to 25.03 cents per liter for petroleum diesel (see Table Five in the Appendix). However, most of the biodiesel cost results from seed transportation, which contributes between 46.04 and 62.25 cents to the total. This suggests that a change in distribution practices could drastically reduce the price of jatropha biodiesel. Furthermore, the cost of the seed cake is cost competitive with petroleum diesel, ranging in price from 8.71 to 11.05 cents per liter of oil (Openshaw 2000). Finally, in contrast to Openshaw's study, a report distributed by Goldman Sachs (Barta 2009) indicated that jatropha biodiesel could be produced at a cost of \$43 per barrel, making it competitive with petroleum diesel and placing it below the cost of biofuels based on other feedstocks, such as sugarcane (\$45 per barrel), corn (\$83 per barrel), and soybeans (\$122 per barrel) (see Table Six in the Appendix).

#### **Income**

Openshaw (2000) estimated that a jatropha plantation could yield an income of \$1,183 per hectare over a six year period (see Table Seven in the Appendix). This is based on a price of \$16 per tonne for the fruit coat, \$25 per tonne for the shell, \$117 per tonne for the seed, and \$25 per tonne for the wood. Additional costs, such as transportation and marketing expenses, were deducted to ensure that the income represents the amount the farmer would receive. Although the coat, shell, and wood prices were based on the use of these items as energy products, Openshaw (2000) based the seed price on the use of the oil for soap making due to his low price estimate for jatropha oil as a petroleum diesel alternative. As noted above, some studies have found jatropha oil to be an economically viable alternative to petroleum diesel. Therefore, it seems additional research is necessary to determine the economic competitiveness of jatropha oil in different market sectors and in different geographic regions.

Given these estimates, Openshaw (2000) calculated that the farmer would realize a gross income of \$585 per hectare per year and a net income of \$394 per hectare per year starting in the sixth year. The net income would fall to \$233 per hectare per year if the farmer sold only the seed. The net income would rise to \$480 per hectare per year if the farmer supplied all of the labor. Assuming a land rental fee of \$100 per hectare per year, the capital return would be approximately 40 percent, which equates to slightly more than \$1 per hectare per day starting in the sixth year. Furthermore, if the fruit were sold entirely for fuel purposes, the net income from the fruit and the wood would fall to \$244 per hectare per year, assuming the farmer supplied all of the labor. Finally, Openshaw notes that these estimates are based on an assumption of high rainfall levels. In the case of a more arid region with less than 500 millimeters of rain per year, the seed yield would fall, resulting in decreased profits (Openshaw 2000).

### **Economics: Additional Services and Products**

#### **Added Value**

According to Openshaw's calculations, a jatropha plantation would offer a very small return to the farmer if jatropha oil were the only product of value. Singh et al. (2008) agrees with this conclusion, noting that jatropha oil constitutes only about 17 to 18 percent of the dry fruit by weight. Therefore, the recent interest in jatropha plantations is due not only to the potential use of jatropha oil as a biofuel but also to the growing evidence that jatropha trees provide a diverse array of services and products that add value to the crop.

#### **The Whole Tree**

The added benefits of jatropha begin with the tree itself. Jatropha is used as a living fence around agricultural fields in some countries, such as Mali and Haiti (Openshaw 2000 and author's observations). The toxicity of jatropha makes it an attractive choice for a live fence since it deters grazing animals from eating their way through the tree line to the fields (Gubitz et al. 1999). Furthermore, jatropha hedges provide a barrier to wind and soil erosion, increasing the fertility of the fields (Openshaw). Presumably, jatropha offers a more economical fencing method than wire or post fences in these locations, although a cost comparison study would be necessary to prove this.

#### **Wood, Roots, and Bark**

Jatropha branches can be used as fuel, but this is not commonly done because the wood is green and difficult to dry, leading to poor combustion (Openshaw 2000 and author's observations). Alternatively, the stalk of the jatropha tree can serve as a support pole for vanilla

plants and other vines (Openshaw (2000)). The roots of the jatropha tree can help control erosion as discussed above and also produce a yellow oil that has potential pharmaceutical applications in treating parasitic worms (Augustus et al. 2002). The bark provides tannin, which is used in the leather industry, as well as a blue dye (Augustus et al. 2002 and Openshaw 2000).

#### **Leaves, Flowers, and Seeds**

Jatropha leaves have been used as silkworm hosts in some countries, but the survival rate of 21 percent is significantly lower than that found with other hosts such as castor leaves (Gubitz et al. 1999). The leaves also produce latex, which is a valuable commodity in the pharmaceutical industry (Augustus et al. 2002). Jatropha flowers attract bees, providing the opportunity for honey production in conjunction with other uses of the jatropha tree (Openshaw 2000). Finally, the seeds can be burned directly, without extracting the oil, to provide an alternative to kerosene lamps (Slavin 2008).

#### **Husk and Shell**

The husk and shell of the jatropha seed are both potential fuels. Singh et al. (2008) found that the chemical composition of the husk (3.97 percent ash, 71.04 percent volatile matter, and 24.99 percent fixed carbon) is similar to that of other biomass energy sources (see Table 8 in the Appendix). In addition, the researchers successfully converted the jatropha husk to producer gas (see Table 9 in the Appendix). In contrast, the same study found that the jatropha shell cannot be easily gasified due to its high ash content (see Table 8 in the Appendix). However, the shell can be converted into briquettes and burned in cook stoves. Furthermore, the ash that remains after shell combustion is high in sodium and potassium, making it suitable for soil enrichment (Singh et al. 2008).

#### **Seed Cake**

Singh et al. (2008) found that 70 to 75 percent of the jatropha seed is left as cake during the oil extraction process, while Staubmann et al. (1997) found that 50 percent of the seed is left as cake. As noted in the section on “Tending Requirements,” jatropha seed cake can be substituted for chemical fertilizers, with 1.0 kg of seed cake replacing 0.15 kg of N:P:K (40:20:10) chemical fertilizer (Prueksakorn and Gheewala 2008). In addition to this use, both Singh et al. (2008) and Staubmann et al. (1997) found that the cake’s high organic matter content makes it suitable for biogas generation. In fact, Singh et al. (2008) found that jatropha seed cake produces 60 percent more biogas than cattle dung. Furthermore, the biogas produced from jatropha cake has more methane than biogas from cattle dung, giving it a higher calorific value

(Singh et al. 2008). Staubmann et al. (1997) calculated a cake-to-biogas conversion time of 4 days for 80 percent of the cake and 7 days for 90 percent of the cake. A third use for the seed cake is to provide animal feed. Although most jatropha varieties are toxic, a few non-toxic varieties of Mexican origin offer a protein-rich seed cake that could make a suitable animal feed (Openshaw 2000).

### **Oil**

Jatropha oil is, of course, used for fuel production. However, other uses for the oil also exist. For example, the oil could be used in the surface coating industry due to its propensity to form a hard film when exposed to air (Augustus et al. 2002). The oil can also be combined with iron oxide to produce a varnish, can be burned in lamps, functions as a lubricant, and has potential uses in the pharmaceutical and pesticide industries (Augustus et al. 2002 and Openshaw 2000). In addition, the non-toxic jatropha varieties could yield an edible cooking oil (Openshaw 2000). Finally, the most well-established and economically significant use of jatropha oil is in the soap and detergent industry, which has used the oil for decades in countries such as India and Zimbabwe (Augustus et al. 2002, Kandpal and Madan 1995, and Openshaw 2000). Glycerin, a byproduct of biodiesel processing, can also be used in the soap industry, as well as the pharmaceutical and cosmetic industries (Singh et al. 2008).

### **Tradeoffs**

Not all of these uses for the jatropha tree are compatible. Therefore, economic tradeoffs must be considered when choosing jatropha varieties, planting methods, and industrial markets. For example, scientists and biofuel entrepreneurs are divided over the preferred jatropha variety since the toxic varieties can be used as living fences, while the non-toxic varieties produce a seed cake that can be used as animal feed (Openshaw 2000). In addition, as noted above, the oil can be used for either fuel production or soap making, while the seed cake can be used for either field fertilization or biogas production. Regardless of the exact choices that are made, the most important decision is to use the tree holistically. As Singh et al. (2008) notes, “If a holistic approach is taken to utilize Jatropha fruit, it will give three times the energy of bio-diesel alone.”

## **Economics: Market Considerations in Developing Nations**

### **Effects on Food Production**

As with the cultivation of most biofuel feedstocks, jatropha cultivation has led to concerns that jatropha might displace food crops. However, unlike some biofuel feedstocks, such as corn and soybeans, most jatropha varieties are inedible and therefore do not create a direct

conflict between the plant's use as a food and its use as a fuel (Agarwal et al. 2007). In addition, jatropha can survive on marginal lands that are inappropriate for food crops, thus reducing the potential for land use conflicts (Openshaw 2000). Furthermore, jatropha can be grown in a beneficial partnership with certain food crops, such as coffee and vegetables, by providing a barrier against grazing animals and restoring degraded soils (Openshaw 2000). Finally, jatropha plantations can exist in partnership with ranching operations since animals will eat the grassy weeds around the trees while leaving the leaves and bark untouched (Openshaw 2000)

Nonetheless, concerns about competition between fuel and food crops should not be categorically dismissed in the case of jatropha. Although jatropha can survive on marginal lands, its productivity diminishes under poor conditions, as explained in the section on "Tending Requirements" (Openshaw 2000, Prueksakorn and Gheewala 2008). Therefore, there is potential for fertile fields to be converted from food crop cultivation to jatropha cultivation. For example, instances of small farmers in India being displaced for the creation of industrial-scale jatropha plantations have been reported (Olden 2007).

#### **Potential Biodiesel Markets**

In developed nations, biodiesel is traditionally targeted toward the automotive industry. However, in developing nations, a wide range of industries use diesel fuel and therefore could be potential biodiesel markets. These applications include: irrigation pumps, grain mills, electrical generators, cooking stoves, rail transportation, and brick processing, (Agarwal et al. 2007 and Openshaw 2000).

#### **Comparative Advantage of Developing Nations**

In some respects, developing nations have a comparative advantage in jatropha biodiesel production. For example, the climate of many lesser developed nations is subtropical to tropical, which not only meets the demands of jatropha cultivation but also provides optimal conditions for biodiesel use and for biogas production since warm temperatures reduce the viscosity of biodiesel and improve the fermentation of seed cake (Agarwal et al. 2007 and Staubmann et al. 1997). As a result of the latter effect, biogas production can occur without the expense of heating in warm climates (Staubmann et al. 1997). These climatic advantages in jatropha production and use could in turn provide the opportunity for technological advancement in developing nations since these countries have an incentive to design the necessary equipment to cultivate, process, and use biofuels. Openshaw (2000) suggests that countries with expertise in biofuels will be in

an economically advantageous position if a global carbon tax is passed or if petroleum prices rise rapidly in response to dwindling supplies.

Another potential advantage of developing nations is the greater decentralization of their economies. In what is termed the “leapfrog” phenomenon, developing nations are often able to pass over some of the capital-intensive infrastructure investments made by developed nations through adopting newer, more dispersed technologies (“Behind the Bleeding Edge” 2006). For example, cell phone use has surged in many developing countries in recent years, rendering the lack of landlines in these countries immaterial (“Behind the Bleeding Edge” 2006). A similar trend could occur in the energy sector if small farmers in developing nations used a portion of their resources to grow biofuel crops for local use in transportation, electricity generation, irrigation pumps, and grain mills. This would reduce the need for investment in nationwide energy networks while still improving the availability of energy for residential and commercial use. The prior existence of decentralized agricultural and banking cooperatives in countries such as Haiti could provide a model for the establishment of energy cooperatives (author’s observations). Prueksakorn and Gheewala (2008) predict that small-scale biodiesel operations will proliferate more rapidly than large-scale operations because the management of biodiesel factories does not require highly technical knowledge and because local fuel production lowers the distribution costs of the fuel.

## **Environmental Considerations**

### **Soil System Effects**

As discussed previously, jatropha trees can help restore degraded soils by holding organic matter in place with their roots and by supplying essential nutrients to the soil system. Of course, soil nutrient build-up only occurs if a portion of the tree’s leaves and seeds are returned to the soil rather than removed for energy generation or other industrial purposes. As with any trees, jatropha can also promote the infiltration of rainwater in an ecosystem, helping to lower peak flood levels, reduce erosion, and encourage the replenishment of groundwater (Neary et al. 2009). By both replenishing groundwater and providing shade, the trees may also help reduce the severity of droughts (Neary et al. 2009). Of course, the intensity of jatropha cultivation will influence the tree’s impact on the soil with greater tree density reducing the nutrients and water available for other crops (Openshaw 2000). Therefore, additional research is needed to determine

the exact effect of jatropha plantations on the soil system, based on different tree densities, fertilization practices, and crop mixes (i.e. intercropping versus monoculture).

#### **Atmospheric Effects**

The atmospheric effects of growing jatropha as an energy source can be divided into two categories: changes in atmospheric gas concentrations due to the cultivation of jatropha trees and changes in atmospheric gas concentrations due to the combustion of jatropha biofuels. In the case of jatropha cultivation, the main atmospheric effect is sequestration of carbon in the tree. This carbon sequestration during the growing phase helps make jatropha biofuels “carbon neutral” since the carbon dioxide released during combustion is sequestered via photosynthesis during cultivation (Agarwal et al. 2007). This offers the potential for jatropha biofuels to play a role in the reduction of greenhouse gas emissions and therefore in the abatement of anthropogenic climate change.

Several studies have compared the emissions of petroleum diesel with those of either pure jatropha oil or jatropha biodiesel. Singh et al. (2008) compared the emissions of petroleum diesel and jatropha biodiesel. Overall, the study found that jatropha biodiesel releases higher amounts of nitrogen oxides but lower amounts of carbon monoxide and hydrocarbons (Singh et al. 2008). Agarwal et al. (2007) examined the emissions of pure vegetable oils relative to petroleum biodiesel and reported that vegetable oils generally release lower amounts of the following pollutants: carbon monoxide, hydrocarbons, sulfur oxides, particulate matter, smoke, and noise. However, in their own tests, these researchers found higher levels of carbon monoxide, hydrocarbons, and smoke in jatropha oil emissions relative to petroleum diesel emissions, although the levels of these pollutants were similar when the jatropha oil was preheated (Agarwal et al. 2007). In addition, Agarwal et al. (2007) found lower levels of sulfur oxides in jatropha oil emissions due to the lower sulfur content of the oil relative to petroleum diesel. Kandpal and Madan (1995) found no sulfur dioxide in the emissions from jatropha oil and approximately the same levels of carbon monoxide in the emissions from jatropha oil and petroleum diesel. Further research should be conducted to explain discrepancies between these results and to verify or modify the estimated emissions from jatropha oil and jatropha biodiesel.

#### **Water Resources Effects**

As noted in the section on “Tending Requirements,” jatropha trees can survive drought conditions (Prueksakorn and Gheewala 2008). Due to this quality, the tree is frequently touted as

a crop requiring few water inputs. However, as was also noted earlier, the tree cannot produce maximum seed yields in drought conditions (Prueksakorn and Gheewala 2008). Therefore, the tree may impose a greater strain on water resources than was previously thought.

A recent study by Gerbens-Leenes et al. (2009) compared the water footprints of a range of biofuel feedstocks, including jatropha. The authors made two general observations: 1) the water footprint of biofuels exceeds that of bioelectricity since a smaller portion of the crop is used in biofuel production, and 2) the water footprint of biodiesel exceeds that of bioethanol. The authors then calculated that soybean has the smallest water footprint among biodiesel crops (13,700 liters of water per liter of biodiesel) while jatropha has the largest water footprint among biodiesel crops (20,000 liters of water per liter of biodiesel). The numbers are further broken down into the green water footprint, referring to rainwater, and the blue water footprint, referring to surface and ground water used in irrigation (see Table Ten in the Appendix). These numbers are based on a weighted-global average and therefore the footprint in a given country will differ based on the local climate and the local agricultural practices. The five countries included in the jatropha calculations are India, Indonesia, Nicaragua, Brazil, and Guatemala. Jatropha's water footprint is the largest in India and the smallest in Brazil. The authors did not deduct the energy inputs of biofuel production (e.g. energy used to run agricultural equipment or to process biofuels) from the energy output of the biofuels. Therefore, the water footprints underestimate the actual water inputs per unit of net energy produced, particularly for crop systems that require large energy inputs (Gerbens-Leenes et al. 2009).

Some jatropha cultivators have disputed the findings of Gerbens-Leenes et al. (2009). For example, according to *The New York Times*, Ruud Van Eck, a Dutch jatropha entrepreneur in Tanzania, found that “the sample size used in the study was small, and focused on projects located in high rainfall areas in Asia” (Browne 2009). Such criticisms illustrate the importance of further improving quantitative techniques for assessing the impact of biofuel production on water resources. By honing our ability to measure the water requirements of biofuel crops, we can make better decisions regarding the appropriate crops for particular regions and the tradeoffs between water use for biofuel crops, food crops, and other sectors. As Gerbens-Leenes et al. (2009) note, 86 percent of worldwide freshwater use is already devoted to agriculture. Therefore, any increase in agricultural production, whether for food, fiber, or fuel, will require more efficient use of existing water resources.

## **Forest Effects**

The exact effects of jatropha cultivation on forests have not been studied. One hope for jatropha is that its oil could be used in cook stoves, thereby reducing the rate of deforestation in rural areas that currently depend on firewood for fuel (Openshaw 2000 and author's observations). However, most deforestation results from agricultural land-clearing rather than wood harvesting (Openshaw 2000). Therefore, increased jatropha cultivation could actually put greater pressure on existing forests by expanding the amount of land used for agriculture. To understand the potential scale of jatropha cultivation, it is helpful to consider that the Zimbabwe soap industry alone would require 20,000 hectares of jatropha to meet its oil demands (Openshaw 2000). If existing forests were cleared as a result of jatropha cultivation, this would result in a loss of biodiversity and of native species, as well as the alteration of critical ecosystem functions such as nutrient cycling. Alternatively, jatropha could be grown alongside other crops in an agro-forestry system or on marginal lands as an aid to soil restoration and erosion control (Openshaw 2000). In these cases, the tree could help mitigate the stress imposed by expanding agricultural production on forest lands.

## **Early Adopters**

### **India**

The Indian government has made jatropha a part of its national energy plan. Termed the "National Biodiesel Mission," the government's jatropha mandate includes two stages:

*1) A demonstration project carried out over the period 2003-2007 aimed at cultivating 400,000 hectares of Jatropha to yield about 3.75 tons oilseed per hectare annually. The project will also demonstrate the viability of other aspects like seed collection and oil extraction. In addition, the government will build a transesterification plant.*

*2) A commercialization period during 2007-2012 will continue Jatropha cultivation and install more transesterification plants which will position India to meet 20 per cent of its diesel needs through biodiesel. (quoted from Gonsalves 2006, pp. 5-6)*

Agarwal et al. (2007) notes that India has a particular interest in substitutes for petroleum diesel because the country uses about six times as much diesel as gasoline. The government has supported jatropha expansion through loans to small farmers (Slavin 2008). In addition, the private sector has entered the Indian jatropha market. In 2007, two British companies D1 Oils and BP formed a joint venture to plant one million hectares of jatropha, primarily in India

(Slavin 2008). Although the partnership has since dissolved, D1 Oils is still heavily involved in jatropha development (D1 Oils 2009). In addition, the Indian company Reliance is not only planting jatropha but also investing in genetic research to design high-yielding varieties of the tree (Slavin 2008). Public-private partnerships include ongoing research into jatropha cultivation at Indian universities and the potential leasing of government land to jatropha developers through the Council on Climate Change's Green India program (Augustus et al. 2007, Kandpal and Madan 1995, and Slavin 2008). Beyond India, other Asian countries, including Thailand and Indonesia, have also begun to grow jatropha for biofuel production (MAP and Openshaw 2000).

Despite the large financial and scientific investments already made in Indian jatropha development, experts dispute whether the Indian jatropha initiative will be successful. For example, although The Energy Resource Institute reported that up to 30 million hectares of marginal land in India could be suitable for jatropha, *The Wall Street Journal* reported that some of the farmers who received government loans have suffered financial losses due to the small yields from jatropha grown on marginal lands (Slavin 2008). The discrepancies may find partial explanation in the rapid push to expand jatropha cultivation before all of the technical concerns have been resolved.

#### **Africa**

Certain countries in Africa, including Burkina Faso, Madagascar, Malawi, Mozambique, Tanzania, South Africa, Zambia, and Zimbabwe, have begun to engage in jatropha cultivation, although the areal extent of jatropha cultivation across the entire continent is probably less than that of India alone ("Biodiesel 2020" 2008). Most investment into African jatropha currently derives from European countries, including such companies as Britain's D1 Oils, Germany's PROKON, and the Netherlands' BioShape (BioShape Holding B.V. 2009, D1 Oils 2009, and PROKON Renewable Energy Ltd. 2009). These companies are developing large-scale plantation programs that cover thousands of hectares ("Biodiesel 2020" 2008). However, not all jatropha initiatives in Africa are led by foreign entities. For example, the Agricultural Research Trust of Zimbabwe has developed test plots of jatropha trees from different countries to test their suitability for local conditions (Openshaw 2000). Such biological research will be critical for the adaptation of jatropha cultivation to the varied climatic and soil conditions in different parts of Africa. Furthermore, socio-economic research will be necessary to ensure that jatropha

plantations are developed in a manner that is compatible with the cultures and existing industries in each African nation.

### **Americas**

Although jatropha originated in the Americas, this region of the world has been slightly slower to join the jatropha biofuel movement. Nonetheless, in recent years, several countries in Latin America have begun to develop small jatropha biodiesel industries. A couple of notable examples are Brazil, which is already renowned for its ethanol industry, and Nicaragua, which started a jatropha research program at the Universidad Nacional de Ingenieria in 1989 with the financial support of the Austrian government (Openshaw 2000 and Gubitiz 1999). Jatropha has also received attention in Mexico due in part to the non-toxic varieties native to that country (Openshaw 2000). As in Africa, much of the investment into jatropha cultivation in Latin America originates in Europe, but U.S. companies and aid organizations have also sponsored jatropha projects in Latin America (D1 Oils 2009 and SG Biofuels 2009). Foreign entities involved in Latin American jatropha development include California's SG Biofuels, Switzerland's Syngenta Foundation, and Britain's D1 Oils, which was recently commissioned by the United States Agency for International Development to conduct a jatropha feasibility study in Haiti (D1 Oils 2009, SG Biofuels 2009, and Syngenta 2009). Some indigenous jatropha programs also exist in Latin America, such as CHIBAS, a Haitian research organization devoted to developing jatropha hybrids that are suited to the Haitian climate and soils (CHIBAS 2009).

### **Developed Nations**

Although jatropha has gained the most attention in developing nations, several industrialized nations have also begun to investigate the tree's potential as a biofuel feedstock. For example, a U.S. company called My Dream Fuel has planted 900,000 jatropha trees near Fort Myers, Florida since 2006 (Padgett 2009). In addition, Air New Zealand recently partnered with Rolls-Royce to develop a 50-50 blend of jatropha fuel and Jet A1 fuel that could power a 747-400 airplane, running a successful test flight in late 2008 (Kanter 2008). As discussed earlier, many developing nations have a comparative advantage in jatropha biodiesel production. This advantage could become increasingly profitable to them as developed nations look for new ways to reduce their reliance on fossil fuels and to diminish their impact on the climate.

## **Future Outlook**

The future of jatropha biofuels depends on a complex set of interactions between science, economics, and politics. Ongoing scientific research is focused on improving plant genetics, enhancing oil extraction through the use of enzymes, and investigating medical uses of the plant (Gubitz et al. 1999). The results of such research will directly determine the economic viability of the plant. In addition, attention must also be paid to the ecological and social equity implications of growing jatropha as a biofuel feedstock since the political feasibility of jatropha biofuels depends strongly on the public's confidence that the plant can be grown in an environmentally and socially sensitive manner. Therefore, research should be conducted to further assess the effects of intensive jatropha cultivation on soil quality, water resources, existing forests, and the welfare of local farmers. Finally, the potential users of jatropha biofuels must have confidence in the fuel's suitability as a petroleum diesel substitute. Therefore, scientifically sound standards should be established for jatropha biofuels to ensure the long-term marketability of the product.

In conclusion, jatropha biofuels offer a promising alternative to petroleum-based fuels, although the expansion of the industry should be closely monitored. The current emphasis on jatropha cultivation as an economic driver in developing nations poses great risks since unexpected setbacks could have a devastating impact on small farmers who are already living on the margin. Yet at the same time, the comparative advantage of developing nations in producing jatropha biofuels presents great opportunities since the advancement of a new energy source could both help these nations meet their own energy needs and give them a valuable commodity to trade on the world market.

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## Appendix

**Table One**

**TABLE 3. NER and Main Energy Contributor of the Life Cycle of JME Production**

source	average result	worst case scenario	best case scenario	(26)	Case 1 (23)	Case 2 (23)
NER	6.03	1.93	11.99	3.74	2.78	2.44
NER (only biodiesel)	1.42	0.53	2.70	0.68		
first contributor	agriculture	transportation	transesterification	lime	transesterification	transesterification
second contributor	transesterification	transesterification	agriculture	oil refinery	cultivation/harvesting	transportation
third contributor	transportation	agriculture	oil extraction	fertilization	oil extraction	cultivation/harvesting

Prueksakorn and Gheewala (2008)

**Table Two**

Table 4a

*J. curcas*: establishment and tending costs (units: US\$ per hectare)<sup>a</sup>

Year	Labour	Fertilizer	Seed	Plough hire	Total
1–5 [sum]	55	153	3	9	220
6 and onwards	21	102	0	0	123
Total 1–6	76	255	3	9	343

<sup>a</sup> Source: [12] and author's estimates. More details are given in the Appendix.

Openshaw (2000)

**Table Three**

*A.1. Establishment costs J. curcas for commercial production (units: \$ per hectare)<sup>a</sup>*

Operation	Labour	Materials/machines	Total	Remarks
Ploughing	0.8	9.0	11.8	Animal drawn plough
Digging pit	6.5	0.0	6.5	1600 pits per ha
Applying FYM (Farmyard manure)	1.5	7.5	9.0	1 kg per hole
Seeding	0.5	2.8	3.3	two seeds per hole
Filling pit	3.3	0.0	3.3	
Weeding	6.5	0.0	6.5	
Applying fertilizer	1.1	20.5	21.6	160 kg NPK, two dressings
Year 1. Initial Establishment	22.2	39.8	62.0	
Year 2. Weeding	6.5	0.0	6.5	
Applying fertilizer	1.4	6.9	8.3	170 kg seed cake
Total year 2	7.9	6.9	14.8	
Year 3. Applying fert.	3.5	16.9	20.4	420 kg seed cake
Year 4. Applying fert.	7.1	33.9	41.9	840 kg seed cake
Year 5. Applying fert.	14.1	67.7	81.8	1680 kg seed cake
Year 6 and onwards. Applying fertilizer	21.2	101.6	122.8	2520 kg seed cake

<sup>a</sup> Labour wage \$1 per day. Cost of seed cake ex-factory \$35/t. Transport to farm \$5/t. Handling \$0.3/t. Spreading \$8.4/t. 1 tonne of seed cake is equivalent to 150 kg. NPK (40:20:10).

Openshaw (2000)

**Table Four**

Table 4b  
*J. curcas*: harvesting costs of fruit and wood (units: US\$ per hectare)<sup>a</sup>

Year	Fruit yield and cost/ha					Wood yield and cost/ha		
	Wt (t)	Collect	De-coat	Shell	Total	Wt (t)	Fell etc.	Total cost (3)
1-5 [sum]	(9.25)	21	21	17	59	(0.0)	0	59
6 and onwards	(7.50)	17	17	14	48	(4.0)	20	68
1-6	(16.75)	38	38	31	107	(4.0)	20	127

<sup>a</sup> Source: [12] and author's estimates. More details are given in the Appendix. Fruit: per air dry tonne. Collection and transport \$2.30. Removing the fruit coat \$2.30. Shelling \$1.84. In terms of the cost per tonne of seed, (Table 6). Collection \$5. Coat removal \$5. Shelling \$4. Wood: thinning, felling, pruning, trimming, cross cutting, hauling and stacking \$5/air-dry t wood. An estimated 95% of the above costs are labour costs and 5% are for tools, sacks and equipment.

Openshaw (2000)

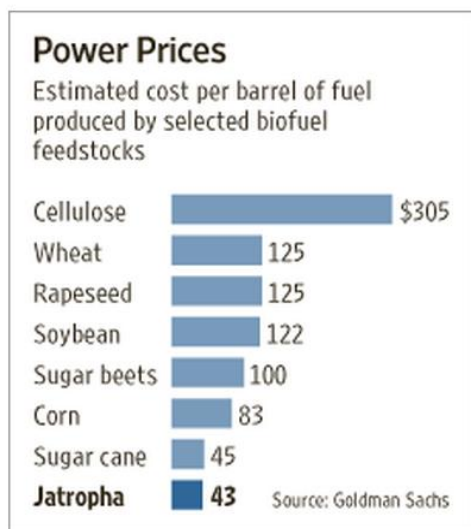
**Table Five**

Table 6  
 The cost of jatropha oil production and the price of competing products<sup>a</sup>

Country	India	Zimbabwe	
	Industrial <sup>b</sup>	Hand press <sup>c</sup>	Motor press <sup>d</sup>
Operating days per year <sup>e</sup>	250	250	250
Input: t of seed/y	1000 <sup>f</sup>	13.75 <sup>g</sup>	184.2 <sup>h</sup>
Output: t seed cake/y <sup>i</sup>	730	10.65	141.93
Output: t plant oil/y	270	3.10	42.32
Output: litre plant oil/y	293,500	3,375 <sup>j</sup>	46,000 <sup>j</sup>
Cost of production per litre (US cents)			
Seed processing	4.77 <sup>k</sup>	5.70 <sup>l</sup>	5.61 <sup>l</sup>
Seed delivery ex-processing	62.25 <sup>m</sup>	46.04 <sup>n</sup>	45.25 <sup>n</sup>
Oil manufacture	5.87	16.44 <sup>o</sup>	14.59 <sup>o</sup>
Total cost	72.89	68.18	65.45
Selling price of substitute products (US cents per litre) <sup>p</sup>			
Kerosene (paraffin)	7.10	11.37	11.37
Diesel	16.57	25.03	25.03
Plant oil/tallow oil	73.60	67.08	67.08
Seed cake (per litre of oil) <sup>q</sup>	8.71	11.05	10.80

<sup>a</sup> Source: [12,13,17-19] and author's estimates.

Openshaw (2000)

**Table Six**

Barta (2009)

**Table Seven**

Table 5  
*J. curcas*: estimated yield and income from the fruit and wood  
 (units: US\$ per hectare ex farm)<sup>a</sup>

Year	Coat	Shell	Seed	Sub-total	Wood	Total
(price \$/t)	(16)	(25)	(117)		(25)	
1-5	44	56	498	598	0	598
6 onwards	36	45	404	485	100	585
1-6	80	101	902	1083	100	1183

<sup>a</sup> Source: [12] and author's estimates. Fruit: for the coat and the shell, the selling price is based on their energy content. The seed price is based on the buying price at the oil factory. This factory sells the oil for soap making. The costs of transport and marketing etc. have been deducted to obtain a farm gate price. The ex-farm selling price of wood is based on its energy content.

Openshaw (2000)

**Table Eight**

Table 3  
 Physical and thermal properties of *Jatropha* seed husk and shell compared to wood, and biomass briquettes

Parameters	Gandabaval wood ( <i>Prosopis juliflora</i> )	Biomass briquettes	<i>Jatropha</i> shell	<i>Jatropha</i> seed husk
Bulk density (kg m <sup>-3</sup> )	407	545	106.18	223.09
Angle of repose (°)	18.8	32.28	26.31	25.03
Moisture content (% wb)	8.81	12.50	12.35	10.75
Volatile matter (% db)	83.23	56.80	68.73	71.04
Ash content (% db)	1.07	08.77	14.88	3.97
Fixed carbon (% db)	15.70	21.93	16.38	24.99
Calorific value (kcal kg <sup>-1</sup> )	4018	4130	3762	4044

Singh et al. (2008)

Cooke (2009)

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### Table Nine

Table 4  
Composition of producer gas obtained from Jatropha seed husk

Gas flow rate (m <sup>3</sup> h <sup>-1</sup> )	Producer gas composition (%)					Calorific value (kcal m <sup>-3</sup> )
	H <sub>2</sub>	CO	CH <sub>4</sub>	N <sub>2</sub>	CO <sub>2</sub> +O <sub>2</sub>	
4.5	14.08	14.05	1.86	57.02	12.99	1067
5.5	10.62	19.26	1.71	57.08	11.33	1105

Singh et al. (2008)

### Table Ten

Table 2. Total weighted-global average WF for 10 crops providing ethanol and 3 crops providing biodiesel (m<sup>3</sup>/GJ), as well as their blue and green WF

Crop	Total WF	Blue WF	Green WF	Total water	Blue water	Green water
Ethanol		m <sup>3</sup> per GJ ethanol			L of water per L of ethanol	
Sugar beet	59	35	24	1,388	822	566
Potato	103	46	56	2,399	1,078	1,321
Sugar cane	108	58	49	2,516	1,364	1,152
Maize	110	43	67	2,570	1,013	1,557
Cassava	125	18	107	2,926	420	2,506
Barley	159	89	70	3,727	2,083	1,644
Rye	171	79	92	3,990	1,846	2,143
Paddy rice	191	70	121	4,476	1,641	2,835
Wheat	211	123	89	4,946	2,873	2,073
Sorghum	419	182	238	9,812	4,254	5,558
Biodiesel		m <sup>3</sup> per GJ biodiesel			L of water per L of biodiesel	
Soybean	394	217	177	13,676	7,521	6,155
Rapeseed	409	245	165	14,201	8,487	5,714
Jatropha*	574	335	239	19,924	11,636	8,288

The table also shows the amount of water needed for a specific crop to produce 1 L of ethanol or 1 L of biodiesel.

\*Average figures for 5 countries (India, Indonesia, Nicaragua, Brazil, and Guatemala).

Gerbens-Leenes et al. (2009)