Ecofys Netherlands BV
P.O. Box 8408
NL-3503 RK Utrecht
Kanaalweg 16-G
NL-3526 KL Utrecht
The Netherlands

W: www.ecofys.com
T: +31 (0)30 280 8300
F: +31 (0)30 280 8301
E: info@ecofys.com

BIO-ETHANOL FROM CASSAVA

Leen Kuiper
Burcu Ekmekci
Carlo Hamelinck
Willem Hettinga
Sebastian Meyer
Klaas Koop

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Preface

The Biomass Upstream Committee (BUS) has organized an annual meeting on November 20, 2007, to discuss a number of interesting opportunities in the field of upstream biomass. Topics have been selected by the BUS participants themselves. The selected themes will contribute to a better understanding of the supply-side of the emerging market for bio-energy and they will be presented in such a way to stimulate an open and lively discussion about the feasibility, sustainability and possible impacts that their deployment may have on the environment.

Ecofys has selected the topic "Bio-ethanol from cassava". Cassava is grown in many countries with a warm and moist tropical climate. Cassava yields well on soils of relatively low fertility where the cultivation of other crops would be uneconomical. Such growth conditions are widely available throughout the Tropics, especially in Africa. Cassava is the third largest source of carbohydrates for human consumption in the world, due to its efficient growth, year round availability, its tolerance to extreme stress and its suitability to be incorporated into traditional low-input farming systems, which predominate in Africa. Recently, the cultivation of cassava for the production of ethanol has been intensified. In situations where water availability is limited (i.e. not enough for the cultivation of sugar cane), cassava is the preferred feedstock for ethanol production.

This new use to make bio-fuels from cassava may affect the development of rural Africa both in a positive and in a negative way, which was the main reason why this quick-scan report looks at cassava cropping and utilisation from different angles: general agronomy, suitability as a feedstock for ethanol production, use of co-products, current status and markets, its economic feasibility in comparison with other ethanol crops and aspects of sustainability. It is the result of a limited quick-scan performed by 6 members of the Bio Energy group at Ecofys, which implies that just an overview of the main issues is presented, without going into much detail.

Utrecht, 30 November 2007

Summary

This paper examines the possibilities for ethanol production from cassava: the cropping system, the technological design of a cassava ethanol plant, the use of waste streams for biogas production, the economics of production, current market and potential for cassava ethanol production and sustainability issues have been addressed.

Cassava cropping

Cassava is a major source of low costs carbohydrates and a staple food for 500 million people in the humid tropics. On infertile land where the cultivation of other crops is difficult cassava still has a reasonable yield. Numerous cassava cultivar exist with differences in e.g. size, yield, shape and starch content. Although cassava can produce a crop with minimal inputs, optimal yields are recorded from fields with average soil fertility levels (suitable for most food crops) and regular moisture availability. Young tubers contain much less starch than older tubers, so harvesting must be delayed until a certain amount of starch is accumulated in the tubers. Because fresh cassava roots deteriorate rapidly and can only be kept in good condition for one or two weeks after harvesting, cassava fields are rarely harvested in one pass.

Technology

The technology of producing ethanol from starch is internationally well developed. Cassava is performing average to good on all processing steps. Under optimal conditions ethanol yield from cassava is the highest of all the main ethanol crops (up to 6 t/ha). Moreover, a cassava ethanol plant requires less complex processing equipment resulting in lower investments.

Waste streams to biogas

Waste stream of cassava-ethanol production can be used for the production of biogas. Root fiber represents 30% of the dry weight organic matter and 20% ends up in the wastewater (stillage). These two sources can be used for biogas production. Per tonne of fresh cassava root theoretically 42 m^3 methane can be extracted and 28 m^3 from the wastewater. The global potential of biogas production from cassava ethanol facilities is approximately 3,000 million m^3 (when assuming theoretically that all ‘industrial’ cassava is used for ethanol production only). This is equal to 105 PJ per year.

Economics

The final costs of ethanol from cassava is the sum of cassava cultivation, cassava processing into dried chips and ethanol conversion. Total ex distillery costs are €0.47 per litre which is about the same as for wheat ethanol. Costs for cassava tuber production contribute most to overall production costs. Taking into account that imports from APC countries face no import tariff, cassava ethanol could sell at competitive prices in Europe.

Markets

The largest cassava market by far is in Nigeria, responsible for 18% of world cassava production. Other important cassava producing countries are Brazil (upcoming), Indonesia, Thailand, Congo and Mozambique (upcoming). Approximately 2% of world cassava is traded, mostly in the form of dried chips or pellets. Cassava is mostly used for food (53%). Feed and seed uses contribute 24% and 22% is used for ‘other uses’ (mainly industrial uses). The latter cassava volumes could be used for ethanol production in the future. This would avoid competition with food. Most countries that have a large potential for cassava growing, already show industrial uses of cassava. These countries are: Benin, Mozambique, Ghana, Nigeria, Indonesia and Thailand. In these countries also cassava ethanol initiatives have been identified, either existing or planned. Currently approximately 100 kton of cassava ethanol is being produced. In the short term this could increase up to 2000 kton if large production facilities in Thailand and China start operating and if Nigeria implements its ambitious plans for future ethanol production. On a global scale 6000 kton of cassava ethanol could be produced per year, when restricting to the share of cassava that is now being used for other industrial purposes.

Sustainability

In order to assure a sustainable supply chain for ethanol from cassava, price increases of cassava for food purposes have to be avoided. This could take place if demand for feed would decrease, but this is not likely to happen. Ethanol production could make additional cassava volumes available by drying the volumes which are now lost due to storage problems. Increasing the yield of existing plantations or the planting of cassava on idle land could provide additional cassava volumes designated to ethanol. For a truly sustainable supply chain ecological criteria have to be addressed, such as carbon storage in previous land use systems, decreased biodiversity, soil quality, water use and water pollution and air quality. Social criteria, such as labour conditions and respect to land right. have to be taken into account as well.

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1 Introduction

1.1 Cassava

Cassava (*Manihot esculenta*), sometimes also called manioc, is the third largest source of carbohydrates for human consumption in the world, with an estimated annual world production of 208 million tonnes. In Africa, which is the largest centre of cassava production, it is grown on 7.5 million ha and produces about 60 million tonnes per year. It is a major source of low cost carbohydrates and a staple food for 500 million people in the humid tropics. On infertile land where the cultivation of other crops is difficult, unless considerable inputs are applied, cassava still has a reasonable yield.

Figure 1 Cultivation of cassava

The plant grows tall, some reaching 15 feet, with leaves varying in shape and size (see Figure 1). The edible parts are the tuberous root and leaves. The tuber (root) is somewhat dark brown in colour and grows up to 2 feet long.

The crop is highly efficient in producing starch, it is year-round available, it is tolerant to extreme stress conditions and it fits nicely within traditional farming systems. Fresh roots contain about 30% starch. Cassava starch is one of the best fermentable substances for the production of ethanol. At the moment sugar cane is the most widely used crop for bio-ethanol in the Tropics, but sugar cane requires a lot of water. Consequently, sites suitable for sugar cane growing are very limited (and on most of them sugar cane plantations have ready been established). A much larges area in the Tropics is available andsuitable for cassava.

However, there are some environmental and agronomic constraints to cassava growing and processing: the crop has a high uptake of nutrients and especially a high demand for potassium. Thus a lack of adequate supply of potassium in the soil may limit cassava yields considerably. Excessive nitrogen fertilization on the other hand, may create a high level of poisonous glycosides in the tuber, making it less suitable for human consumption. Furthermore, weed competition can be very detrimental to cassava growth during the initial 3 months after planting, until it has formed a more or less closed canopy. Cassava is rather drought tolerant, except in the first few weeks after planting, when it requires ample soil moisture. On clay soils or poorly drained soils, root growth is poor and root rot is frequent. Gravelly or stony soils are unsuitable for cassava growing, because these soils tend to hinder root penetration. Thus it thrives best on light sandy loams with good drainage. Yet on these “ideal” soil types other food crops can be grown as well, which could imply some serious competition, which puts some question marks to the sustainability of the supply chain.

Figure 2 Cassava tubers

In each locality where the crop is grown, numerous cassava cultivars exist, with different leave sizes, plant heights, colours, tuber shape (see Figure 2), timing of maturity, overall yields, dry matter content, starch content and cyanogenic glycoside content of the roots. Roots with irregular shapes are more difficult to harvest and to peel, resulting in greater losses of usable root material. Traditionally, cassava roots are processed by various methods into numerous products, which are utilised in various ways according to local preferences.

Main industrial uses of fresh cassava roots are for the production of chips, pellets and starch. Recently, cassava has started to be used for bio-ethanol production too (Table 1).

Table 1. Demand of fresh cassava roots for industrial purposes in Thailand in 2007.

Current industries	Ethanol industry	Total demand	Unit
19.15	2.14	21.29	Million tonnes/year

In Chapter 6 current uses and markets of cassava are described in more detail and initiatives that deal with cassava ethanol are presented.

1.2 Conversion factors

Because of the high starch content cassava is a high yielding ethanol crop. However, a distinction has to be made between yields from dried cassava chips and fresh cassava roots. For one kilogram of cassava chips, approximately two kilograms of fresh cassava roots are required. One litre of ethanol can be produced from:

- 5 - 6 kg of fresh roots (containing 30% starch)
- 3 kg of cassava chips (14% moisture content)

On a per tonne cassava basis:

- 1 tonne of fresh cassava roots yields 150 litres of ethanol [1]
- 1 tonne of dry cassava chips yields 333 litres of ethanol

Cassava tuber has the following composition:

- Peel 10-20%
- Cork layer 0.5-2%
- Edible portion 80-90%, of which:
    - Water 62%
    - Carbohydrate 35%
    - Protein 2%
    - Fat 0.3%
    - Fibre 1%
    - Ash 1%

1.3 Structure of the report

Chapter 2 deals with the cropping system, yields and processing of cassava. In Chapter 3 the technology is described for producing ethanol from cassava. The use of waste stream of cassava ethanol production are treated in Chapter 4. Economics of cassava ethanol are described in Chapter 5. Then in Chapter 6 current cassava markets are identified and an inventory is made of cassava ethanol initiatives. Sustainablity issues are addressed in Chapter 7. Finally, results are summarized in Chapter 8.

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[1] However, a recent study in Indonesia assumes that 1 ton of cassava yields about 155 liter of anhydrous ethanol (FAS/Indonesia, 2007)

2 Cropping systems and yields

Cassava, sometimes called manioc, is a tropical root crop. Traditionally it is grown in a savannah climate, but is can grow in a wide range of rainfall conditions (1000-2000 mm/a). In dry areas it looses its leaves to conserve moisture and produces new leaves when rains resume. Under adverse growth conditions it takes about 18 months to produce a crop; under favourable conditions it takes 8 months. Cassava tolerates a wide range of soil pH (4.0 to 8.0). It grows best in the full sun. Under most favourable conditions, yields of fresh roots can reach 40 tonnes/ha[2], while average yields from low-input subsistence agriculture are 10 tonnes/ha.

2.1 Cassava growing

In traditional agriculture, the most common form of seedbed preparation for cassava planting is on mounts or on unploughed land. On unploughed land, no tillage is done other than required to insert the stem cuttings into the soil. The soil can e.g. be opened up with a machete or hue. In improved agriculture, the land is first ploughed and than harrowed. Thereafter cassava may be planted on the flat, on ridges or in furrows. Flat plantings of cassava seem to produce higher yields of tuber than ridge or furrow plantings. However, flat planting is unsuitable on heavy clay soils, because the tubers tend to rot.

Cassava is propagated vegetatively as clones. Generally, cuttings are taken from the mature parts of the stems, which give a better yield than those taken from the younger portion of the stems. The cuttings should have at least 3 nodes, which serve as origins of shouts and of roots. Recent releases from agricultural breeding programmes include clones with resistance to many of the major diseases and pests. Cultivar names are usually based on pigmentation and shape of the leaves, stems and roots. Cultivars may vary in yield, root diameter and length, disease and pest resistance levels, time to harvest, temperature adaptation. Storage root colour is usually white, but a few clones have yellow-fleshed roots. Each region has its own special clones. Most farmers grow several clones in a field.

Cassava is planted using 10-30 cm portions of the mature stem as propagules. These stem cuttings are sometimes referred to as “stakes”. The cuttings are planted by hand in moist, prepared soil, burying the lower half. In Brazil mechanical planters have been developed to reduce labour costs. Obviously, the top of the cuttings has to be placed up. Typical plant spacing is 1 x 1 m (i.e. 10,000 plants/ha). In areas of high soil fertility and high rainfall the plants should be spaced further apart. In Kenya and Uganda, cassava is al-

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[2] In Brazil, in intensely managed field trial even yields of 80 tonnes of tubers/ha have been reported

ways accompanied by intercrops such as maize, beans, millet and sesame. In traditional agriculture where intercropping is practised, planting is often delayed until the later part of the rainy season when the intercrops are nearly ready for harvest.
Cuttings produce roots within a few days and new shoots appear soon afterwards. Early growth is relatively slow, thus weeds must be controlled during the first few months. Although cassava can produce a crop with minimal inputs, optimal yields are recorded from fields with average soil fertility levels (suitable for most food crops) and regular moisture availability.

Cassava responds well to P and K fertilisation. Vascular-arbuscular mycorrhizae benefit cassava by supplying phosphorus to the roots. High N fertilization (more than 100 kg N/ha), however, may result in excessive foliage production at the expense of root development. Fertilizer is only applied during the first few months of growth. Plants are ready for harvest as soon as the storage roots are large enough to meet the requirements of the consumer. Typically, harvesting can begin eight months after planting. In the tropics, plants can remain unharvested for more than one growing season, allowing the storage roots to enlarge further. However, as the roots age, the central portion becomes woody and inedible.

2.2 Harvesting

Most cassava is harvested by hand, lifting the lower part of the stem and pulling the roots out of the ground. The roots are than removed from the base of the stem by hand. Frequently before harvest, the upper parts of the stems with the leaves are cut off to a few centimetres from the ground. In Brazil and Mexico a mechanical harvester has been developed and mechanical harvesters are being tested out in other parts of the world as well. It grabs onto the stem and lifts the roots from the ground. During the harvesting process, care must be taken to minimize damage to the roots, as this greatly reduces shelf life. During the harvesting process, the stem cuttings for the next crop are selected. Young tubers contain much less starch than older tubers, so harvesting must be delayed until a certain amount of starch is accumulated in the tubers. Because fresh cassava roots deteriorate rapidly and can only be kept in good condition for one or two weeks after harvesting, cassava fields are rarely harvested in one pass. The best timing of harvesting depends on the cultivar, but usually ranges from 10 to 24 months. Table 2 gives an idea about cassava cultivation costs in Thailand, which total 294€/ha, at an average yield of 17 tonnes/ha (i.e €17.7/tonne). Farmer sales price for the cassava roots is €28.3/tonne.

Table 2. Costs of cassava growing in Thailand in 2005 (Source: Office of Agricultural Economics, 2005[3])

Variable costs	**255**
1. Labour costs	**150**
- land preparation	37
- planting	18
- weed cortrol	45
- harvesting	50
2. Material costs	**82**
- planting stock	25
- fertilisers	36
- herbicides	18
- fuel	0.8
- other	0.5
3. Miscellaneous costs	**23**
- maintenance and reparation	0.2
- interest	23
Fixed costs	**39**
- Land rent	36
- Depreciation	2
- Interest	1
Total production costs (€/ha)	**294**
Production cost per tonne	17.7
Yield in tonnes/ha	17
Sales price/tonne	28.3

2.3 Processing

The shelf life of fresh cassava roots is only a few days. Removing the leaves two weeks before harvest, increases the shelf life to two weeks. Traditional methods to keep the roots in good condition include packing the roots in moist mulch. The roots can also be dipped in paraffin or in wax or stored in plastic bags. Fresh roots for human consumption can be peeled and frozen. Fresh roots can be sliced thinly and deep fried to make a product similar to potato chips. Dried roots can be milled into flour, which can be used for baking breads. Typically, cassava four may be used as partial substitute for wheat flour in making bread.

Cassava chips industry

In Thailand, which exploits the industrial prospects of cassava on a large scale, cassava chip factories usually are small-scale enterprises, located in close proximity to the cas-

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[3] Sriroth, K et al. 2006. Present situation and future potential of cassava in Thailand.

sava growing area. They use simple equipment consisting mainly of a chopper. Roots are loaded into the hopper of the chopping machine by tractor. After chopping the roots into small pieces, the chips are sun-dried on a cement floor. During drying, which typically requires 2-3 days, a vehicle with a special tool for turning over the chips is used to ensure uniform drying. When it starts raining, chips must be quickly pushed into piles and covered with plastic. This prolongs the drying time and inevitably results in lower chip quality. The final moisture content should be 14%. It takes 2 to 2,5 kg of fresh roots to produce 1 kg of chips. Sun drying of peeled cassava is practised too in many parts of Africa. This method has the advantage that it reduces the cyanogenic glucoside levels from 400 to 56 eq/kg dry weight.

Figure 3 Cassava drying

Pellets industry

Dried Chips are usually sold to pellet manufacturers, who either directly export the chips/pellets or sell to traders. Most factories in Thailand do not have silos for storage. Thus, time from purchase of dried chips to their sale is short. Some portions of cassava chips are used locally for animal feed or as a feedstock for bio-ethanol production. Exports to Europe are mainly in the form of hard pellets rather than chips (see Table 3).

Table 3 Exports of cassava products from Thailand in 2004

Chips	Hard pellets	Starch	Total	Unit
2.57	2.01	1.77	6.36	Million tonnes

The development of a cassava pellet industry in Thailand was stimulated by a need to improve the uniformity in shape and size of cassava chips required by the animal feed producers. In addition, loading and unloading of cassava chips caused serious air pollution, putting pressure in the importers in Europe to improve the handling methods.

Chips are grinded followed by steam extrusion. Upon cooling hard pellets are created. The cassava chips used for pellet manufacture are purchased from drying yards; pellet factories do not produce chips themselves. There are about 200 pellet factories in Thailand with a total capacity of about 10 million tonnes per year. However, the EU export quota is only 5 million tonnes and this is the sole market for the product. Thus the Thai pellet factories are only working at 50% of their capacity.

Starch industry

Cassava starch may be produced from fresh roots, by grating the roots, mixing with water, followed by sedimentation and sun-drying or by conductive heating. The strong increased demand for cassava starch has lead to a modern starch manufacturing process, in which the processing time from the grating of fresh roots to dried starch is less than 30 minutes. About 4.8 tonnes of fresh roots produce one tonne of dry starch. 40 percent of the cassava starch produced in Thailand is used domestically (800,000 tonnes) and 60% is exported by the Thai Tapioca Flour Industries Association. In 2004 about 1.77 million tonnes of starch was exported. Of the various cassava-based products mainly cassava starch and pellets are exported. In the future, starch exports are expected to increase in volume due to the international starch market expansion.

Diseases

About 30 diseases of cassava are known. In many regions cassava is normally not much affected by diseases or pests. However, in other areas it may be attacked by virus diseases (mosaic, brown streak and leaf curl viruses) and bacterial diseases such as *Phytomonas manihotis, Bacterium cassava* and *Bacterium solanacearum.* In Africa the cassava mealybug (*Phenacoccus manihoti*) and cassava green mite (*Mononychellus tanajoa*) can cause up to 80% crop loss, which is extremely detrimental to the production of subsistence farmers. These pests were rampant in the 1970s and 1980s but were brought under control following the establishment of the Biological Control Centre for Africa. The cassava mosaic virus causes the leaves of the cassava plant to wither, limiting the growth of the root. The virus is spread by the whitefly and by the transplanting of diseased plants into new fields. Sometime in the late 1980s, a mutation occurred in Uganda that made the virus even more harmful, causing the complete loss of leaves. This mutated virus has been spreading at a rate of 50 miles per year, and as of 2005 may be found throughout Uganda, Rwanda, Burundi and Congo.

2.4 Agronomic Research & Development

The development of high-yielding varieties of cassava has significantly increased production in many countries. In Ghana, the introduction of improved varieties helped boost the cassava harvest by nearly 40 percent between 1980 and 1996. The International Center for Tropical Agriculture (CIAT) and the International Institute of Tropical Agriculture (IITA) are playing a leading role in developing improved cassava varieties and preserving the genetic diversity of this important staple crop[4]. On average, African farmers produce about 10 tonnes of cassava per hectare, but yields can reach as high as 40 tonnes per hectare. It is estimated that the introduction of high-yielding varieties, improved pest and disease control and better processing methods could increase cassava production in Af-

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[4] http://www.fao.org/NEWS/2000/000405-e.htm

rica by 150 percent. In a recent article in Plant Biotechnology Journal[5] it was reported that cassava has one of the highest rates of CO_2 fixation and sucrose synthesis for any C_3 plant. With this in mind, researchers from Ohio State University develop transgenic cassava with starch yields up 2.6 times higher than normal plants by increasing the sink strength for carbohydrate in the crop. This means cassava makes a 'super crop' when it comes to both CO_2 fixation and carbohydrate production. Commercial cassava producers and processors need to find ways of increasing production, reducing labour costs and improving product quality in order to be able to compete with grains.

In Africa and Latin America, the domestic market for cassava-based animal feed shows potential for growth. More than 30 percent of the cassava produced in Latin America is used for domestic animal feed, compared to less than 2 percent in Africa. Research in Cameroon has shown that poultry breeders could lower their production costs by 40 percent by incorporating cassava into their chicken feed.

In Asia, Thailand leads the way in the production of starches derived from cassava. Cassava starch has unique properties, such as its high viscosity and its resistance to freezing, which make it competitive with other industrial starches.

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[5] Plant Biotechnology Journal, Volume 4/Issue 4, July 2006

3 Ethanol production technology

3.1 Introduction

Ethanol is traditionally produced from feedstock high in sugar and/or starch content. A third possible feedstock is lingo-cellulose. These obsolete feedstocks are attractive, but the technology to convert cellulosic material to ethanol (sometimes referred to as 'second generation') is not yet commercially available. Most used feedstocks for fuel ethanol are wheat, corn, sugar cane and sugar beet. The sugars can be fermented to ethanol, while starch first has to be hydrolyzed to obtain free sugars. Next, the sugars are fermented to ethanol which is followed by a purification step yielding pure ethanol.

The process of extracting starch from cassava is a well-known technology. Cassava has been used as source of starch for decades. Cassava is high in starch content (70 – 85%, dry base / 28 – 35% wet base) and the starch from cassava is of a high quality compared to other starch sources. Cassava starch is used as raw material in many industries, among which paper-, food- and textile industries. Also the technology of producing ethanol from starch is internationally well-developed.

3.2 Process description

After harvesting, the roots are chopped into chips and transported to drying floors. The roots are usually dried in the sun. Once the chips are dried, they can be stored for months. However, during storage, the starch yield decreases somewhat, depending on storage temperature: typically 5% reduction of starch yield in 8 month storage (Abera et al, 2007). Another advantage of chips is the easy transport.
A big advantage of cassava over many other traditional crops is that it can be grown and harvested throughout the year. This results in a constant supply of cassava to the ethanol production facility in contrast to more seasonally crops.

The ethanol production process consists of three basic steps are (Table 4).

Table 4: Main steps in ethanol production from starch

Step	Goal	Type of process
Milling and liquefaction	Breaking down starch molecules into its building block molecules: glucose	Enzymatic
Fermentation	Convert glucose to ethanol	Yeast
Purification	Separate ethanol from other reaction products and inert materials	Distillation

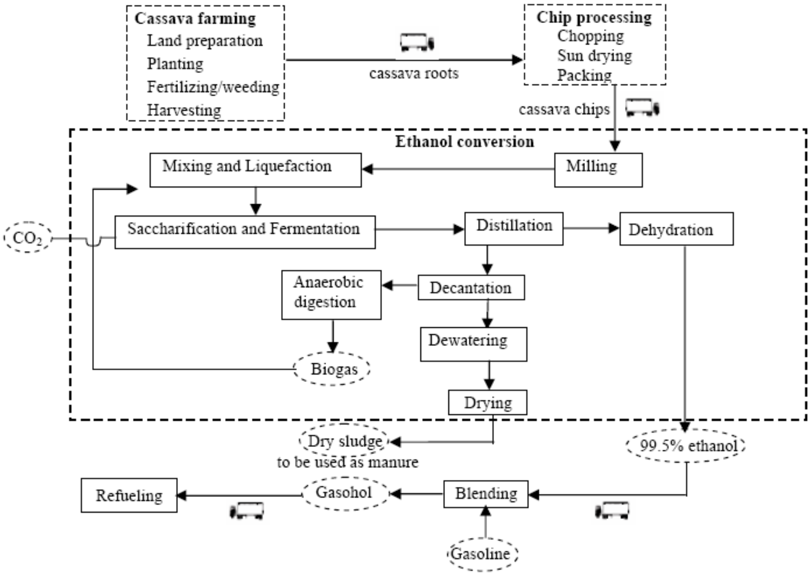

Figure 4 Flowchart of Cassava ethanol production (Nguyen, et al. 2006).

On an industrial scale, the process described in Table 4 is carried out with two distinguishable technologies[6]:

1. Wet milling process
2. Dry grinding process

The two processes differ with respect to complexity and associated capital costs, the numbers and types of co-products produced, and the flexibility to produce different kinds of primary products. The principal differences between the ethanol dry-grind process and the wet mill process are the feedstock preparation steps and the numbers and types of co-products recovered. Once the starch has been recovered the process of converting it to fuel ethanol and recovering the ethanol is similar in both wet mill and dry-grind facilities. Currently, most new facilities use the dry grinding process.

The wet milling process starts with soaking the cassava chips in an acid to soften the material which results in the separation of starch from other components. The fibres are recovered in several separation steps. Next the starch and protein are separated. In this process the steams are fractionated and several co-products can be recovered. Most streams are recovered before the fermentation step.

The dry grinding process starts with grinding the chips. This is done by hammer mills or roller mills. Next the ground material is mixed with water, cooked and mixed with enzymes. This process produces only one co-product that is separated at the end of the

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[6] Apart from dry grinding and wet milling, a third (less applied) technology exists: dry milling.

whole process, after fermentation: distiller dried grains with solubles. This is mostly used as animal feed. The use as animal feed is, however, limited due to the high fibre content.

3.3 Comparison with current commercial crops

The process of producing ethanol from cassava is almost the same as for starchy crops like corn and wheat. However, there are also some differences in the processing.

The ethanol yield is determined by the efficiencies of several consecutive processing steps along the production chain. These factors differ from crop to crop. There is not a single crop performing best at all these steps. Cassava is performing average to good on all steps, resulting in an excellent overall efficiency (Table 5).

Table 5: Comparison of ethanol yield from different crops (reproduced from Wang, 2007)

Crop	Yield (tonne/ha/yr)	Conversion rate to sugar/starch (%)	Conversion rate to ethanol (L/tonne)	Overall ethanol yield (kg/ha/yr)
Cassava	40[7]	25	150	6000
Sugar cane	70	12.5	70	4900
Corn	5	69	410	2050
Wheat	4	66	390	1560

Table 5 shows that under optimal conditions the ethanol yield of cassava (in kg/ha/a) is the highest of all the main ethanol crops. Moreover, a cassava ethanol plants requires less complex processing equipment resulting in lower investments. This is due to the unique characteristics of cassava starch (Wang, 2007) and the low amounts of impurities which makes the extraction of starch from the root, relatively easy.

3.4 Green house gas performance

A complete life cycle analysis (LCA) for the production of ethanol from cassava would be necessary to determine the greenhouse gas (GHG) performance of cassava ethanol. However, this is beyond the scope of the present study. Instead, the results of a recent study (Nguyen, 2007) on the GHG-performance of cassava ethanol in Thailand have been analysed.

GHG-emissions take place in every step of the production chain. The main steps are summarized in Table 6.

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[7] This assumes a rather optimistic yield of 40 tonnes/ha. Currently, in most subsistence farming systems an avergae yield of 10-15 tones/ha is achieved.

Table 6: GHG-emissions in the production of ethanol from cassava

	Main GHG-emissions
Cassava farming	Use of fertilizers (N_2O-emissions) and herbicides Use of fossil fuels (farming equipment)
Cassava transport	Fossil diesel for trucks
Cassava processing	Electricity (generated with fossil fuels) and fossil fuels like natural gas
Ethanol transport	Fossil diesel for trucks

The Nguyen study has made a comparison with several other ethanol production processes based on different crops. The main results are shown in Table 7.

Table 7: GHG-emission reduction (compared to gasoline) of ethanol from different crops (adapted from Nguyen, 2007)

GHG-reduction compared to fossil gasoline	%
Cassava in China	23.3
Cassava in Thailand	62.9
Corn in the USA	48.4
Sugar cane in Brazil	90.9

From Table 7 can be derived that the GHG-performance of cassava ethanol shows a rather wide range (23.3 – 62.9% reduction). Similar ranges were found in many other studies on more common crops such as corn en wheat. Table 7 suggests that cassava ethanol can compete with corn ethanol produced in the USA in terms of GHG emission reduction. To optimize GHG reduction, strict regulations are required (see Chapter 7 on sustainability).

4 Cassava ethanol waste to biogas

This chapter explores the possibilities of using cassava ethanol waste streams for biogas production. Two options are assessed: biogas from ethanol stillage and biogas from root cake (cassava pulp).

4.1 Characteristics of waste streams

The production of ethanol from biomass, whether from sugar crops (sugar beets, sugar cane, molasses, etc.), starch crops (corn, wheat, rice, cassava, etc.), dairy products (whey) or cellulosic materials (crop residues, herbaceous energy crops, bagasse, wood, or municipal solid waste) causes the concurrent production of stillage that shows a considerable pollution potential (Sheehan and Greenfield, 1980; Wilkie et al., 2000). Stillage (also termed distillery waste water, distillery pot ale, distillery spent wash, dunder, mosto, vinasse and thin stillage), is the aqueous by-product from the distillation of ethanol following fermentation of carbo-hydrates.

A mass balance for cassave shows the following results with respect to available organic material from the processing of cassava roots: 1 ton of fresh root contains 400 kg dry matter. During processing about half of this amount is recovered as starch. Root fiber represents 30% of the organic matter and 20% ends up in the wastewater (stillage).

When assuming a COD[8] to dry matter ratio of about 1:1, per ton raw cassava root theoretically 42 m^3 methane (1.5 GJ) can be extracted and 28 m^3 from the wastewater (1.0 GJ). Of course, we have to take into consideration that the root fiber is more 'digestible' than the wastewater, with COD conversion efficiencies ranging from 60-90% for the stillage (depending on composition and other factors) and up to 95% for the root fiber.

For each liter of ethanol produced, up to 20 liters of stillage may be generated (Wilkie et al., 2000). The characteristics of the stillage vary considerably according to the fermentation feedstock and to location. In addition to this, wash water used to clean the fermenters, cooling water blow down might contribute as well to stillage variability (Wilkie et al., 2000; Sheehan and Greenfield, 1980; Pant and Adholeya, 2007).

In general, stillage has low pH, high temperature, dark brown colour, high ash content and high percentage of dissolved organic and inorganic matter (Beltran et al., 2001). The biochemical oxygen demand (BOD) and chemical oxygen demand (COD) range between 35,000 – 50,000 and 100,000-150,000 mg/L, respectively (Nandy et al., 2002). Table 8 shows the distillery wastewater characteristics for cassava.

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[8] COD= cemical oxigen demand; BOD = bio-chemican oxigen demand

Table 8 Characteristics of distillery waste water for cassava feedstock

Characteristics	**Cassava**	
	(Jackman, 1977; Sheehan and Greenfield, 1980)	(de Menezes, 1989; Wilkie et al., 2000)
Stillage Yield (L/L EtOH)	-	16 - 20
BOD (mg/L)	-	31,400
COD (mg/L)	-	81,100
pH	-	3.5
Organic Matter (g/L)	21,800	-
Total Nitrogen (mg/L)	400	650
Sulphate (SO_4^{2-}) (mg/L)	100	-
Calcium (CaO) (mg/L)	100	-
Phosphorus (P_2O_5) (mg/L)	200	-
Total Phosphorus (mg/L)	-	124
Magnesium (MgO) (mg/L)	100	
Potassium (K_2O) (mg/L)	1,100	-

Observations in the cassava-to-ethanol industry in South East Asia have highlighted the variability in the strength of the stillage, with COD ranging from 40,000 to over 200,000 mg/L, total organic content ranging from 100,000 to 150,000 mg/L, suspended solids concentrations from about 6,000 to 30,000. In most cases sulphate levels in the stillage are high, ranging from 2,000 to 7,000 mg/L, as a result of the use of sulphuric acid during the manufacturing process.

4.2 Biogas production from stillage

Anaerobic treatment is the first treatment step for distillery wastewater. A significant portion of COD can be converted to biogas by anaerobic digestion. According to recent studies, anaerobic biological treatment is widely applied as an effective step in removing of up to 90% of the COD in the distillery effluent stream (Wolmarans and de Villiers, 2002). Similarly, 80-90% BOD removal can be obtained. Biochemical energy recovered is 85-90% as biogas (Pant and Adholeya, 2007).

Because of the high organic content of stillage, anaerobic digestion has a prospect of financial return from methane production. By operating the digester with adequate residence time, up to 90 % of the BOD can be removed. The produced gas could supply 30 % of the fuel requirements of distilleries operating on cassava (Willingthon and Marten, 1982).

Wilkie et al. (2000) has made a comprehensive review for anaerobic treatment of different kind of feedstock (Table 9).

Table 9 Mesophilic anaerobic treatment of stillage from conventional feedstocks

Feedstock	Reactor Type	Influent COD (g/L)	HRT (days)	ORL (g COD/L/day)	Treatment Efficiency % Removed COD	Methane Yield (L/g COD)
Barley and sweet potato	2-UASB	29.5	1.2	25	90	0.28
Corn (thin stillage)	ACR	16	5	3.2	97.3	nd
Mixed (potato, beets, wheat, and corn)	UFF	20-55	5	10	75-95	0.3
Potato and beet	UFF	40	4	10	90	nd
Cane Molasses Stillage	DFF	57	4	15	85	0.22

nd: no data; ACR: Anaerobic contact reactor; CSTR: Continuously stirred recator; DFF: Downflow fixed film; UASB: Upflow anaerobic sludge blanket; UFF: Upflow fixed film; 2-UASB: 2 stage UASB

Table 89, summarizes mesophilic anaerobic treatments of several feedstocks in different kinds of reactor types are shown. Because in the literature no specific data is found on cassava ethanol stillage, the results of ethanol stillage for similar feedstocks is used for the assessment of treatment efficiency, suitable reactor type and methane yield.

In Table 10 mesophilic and thermophilic anaerobic treatments are compared with respect to treatment efficiencies and methane yields.

Table 10 Summary of anaerobic treatment of stillage from conventional feedstocks (Modified data from Wilkie et al., 2000)

Temperature/Feedstock	OLR (g COD/L/day)	Treatment Efficiency % removed BOD	Treatment efficiency % removed COD	Methane Yield (L/ g COD)	Methane Productivity (L/L/day)
Mesophilic/molasses	12.25	79.33	71.20	0.26	3.84
Mesophilic/other	12.16	nd	87.25	0.25	2.90
Thermophilic/molasses	23.50	89.20	60.73	0.17	3.37
Mixed/cellulosic	9.48	93.73	83.56	0.30	2.37

nd: no data

Literature study indicates that the treatment efficiency and organic loading rate are dependent on the feedstocks as well as reactor types. According to the research done by Pant and Adholeya (2007), the highest BOD removal is possible in open lagoon whereas the most methane is produced in an upflow anaerobic sludge blanket (UASB) type reactor. On the other hand, the research done by Wilkie et al. (2000) shows that the highest BOD/COD removal can be obtained by using an anaerobic contact reactor, while the highest methane yield is reached by using an upflow fixed film reactor.

The methane yield of the stillage ranges between 0.22 and 0.30 for mesophilic anaerobic treatment. The methane yield and treatment efficiency for thermophilic anaerobic treatment is lower than mesophilic ones.

4.3 Biogas production from cassava pulp

Cassava pulp (also called root cake) is a residue which remains after the extraction of starch from the grinded root. The material consists of fine particles and can be easily digested. Root cake has a dry matter content of about 20%. Own research has shown that the COD equivalent of pulp ranges between 1.0 and 1.3 kg per kg dry matter. This would translate in about 350-450 m^3 methane per ton dry matter or 580-750 m^3 biogas. In other words, the calculation suggests that 70 m^3 methane can be extracted from one ton cassava pulp.

Based on a literature study and practical experience of Ecofys, the potential of biogas production from cassava with respect to the cassava growing region has been analysed. The biogas potential is estimated by taking the share of cassava production that goes to 'other purposes' (see Chapter 6), which is mostly for industrial uses. In the future these amounts of cassava could become available for ethanol production. In this way ethanol can compete with other industrial uses (e.g. starch production) and will not compete with uses for food and feed, which would have consequence for the sustainability (see Chapter 7). Countries have been selected that show large cassava-ethanol potential. With these numbers the potential production of biogas from stillage and pulp can be calculated. Table 11 summarizes the potential biogas production which can be obtained from ethanol stillage and from cassava pulp, respectively.

Table 11 Potential Biogas Production world-wide based on ethanol industry capacity

Region	Annual Cassava production for ethanol industry (10^6 tonnes/year)^a	Biogas from Ethanol Stillage (10^6 m^3 CH$_4$/year)^b	Biogas from Pulp (10^6 m^3 CH$_4$/year)^b	Total Biogas Potential (10^6 m^3 CH$_4$/year)^b
Angola	2.7	76	113	189
Benin	1.3	36	55	91
Brazil	5.2	146	218	364
China	4.4	123	185	308
Congo, The	0.6	17	25	42
Ghana	3.7	104	155	259
Indonesia	6.5	182	273	455
Mozambique	6	168	252	420
Nigeria	14.8	414	622	1,036
Thailand	2.1	59	88	147
World	46.3	1,296	1,945	3,241

a The annual cassava production for ethanol industry is based on the data from Chapter 4 (Table 1). The data listed as "other uses" is assumed to be used entirely for ethanol production.

b The conversion efficiencies are not considered in this calculation.

Table 11 indicates that potential biogas production from cassava pulp is higher than biogas from stillage due to the higher methane yield from the pulp fraction. The global potential of biogas which can be obtained from cassava ethanol production facilities is approximately 3,000 million m^3. Nigeria has the highest relative contribution with 1,000 million m^3 /a of biogas potential, which is followed by Indonesia and Mozambique with a 455 and 420 million m^3 /a of biogas potential, respectively.

5 Economics

5.1 Cassava ethanol production costs

Economic analyses on cassava ethanol production are scarce. The core part of this section is based on one study, by Nguyen et al. (2006) for Thailand.

For the African context, we assume that the industrial parts of the supply chain will eventually have similar efficiencies and costs, since the technology could be imported from other countries. On the agricultural part of the supply chain, initially lower yields can be expected, but it is not clear how this will impact the feedstock costs. Therefore, we assume that the Thailand analysis can be used as an example for cassava ethanol production in Africa, but that the results should be used with care. Additional research would be needed to judge the viability of cassava ethanol in Africa.

The cost of cassava ethanol is the sum of the following process costs:

- Cassava cultivation. This involves land preparation, planting, crop maintenance (fertilization, weed control), and harvesting
- Cassava processing into dried chips.
- Ethanol conversion, milling, mixing and liquefaction, saccharification and fermentation, and distillation/dehydration.

The supply chain is schematically represented in Figure 4.

The costs of cultivation, processing and ethanol production are summarized in Table 12.

Table 12. Cost analysis of cassava ethanol; all data stem from Nguyen et al (2006).

	Specific costs and conversion efficiencies		**Ethanol production cost (€/litre ethanol)**
Production costs of cassava roots[1]	20.1 – 23.5	€/tonne roots	0.164
Profit for farmers[2]	3.8 – 8.8	€/tonne roots	0.047
Cassava chips yield[3]	0.4	tonne chips/tonne roots	
Processing costs[3]	3.4	€/tonne chips	0.010
Profits, margins, transportation[4]	12.4– 18.5	€/tonne chips	0.046
Ethanol yield[5]	333	l ethanol/tonne chips	
Processing costs[5]	0.131	€/l ethanol	0.131
Margin[5]	0.075	€/l ethanol	0.075
Ethanol ex distillery			**0.473**

[1] The production costs of cassava roots are estimated to range 980 – 1,140 THB/tonne.
1 Thai Baht$_{2006}$ = 0.0206 Euro$_{2006}$ (X-rates 2007).

2) Farmers get an average profit of about 183 to 427 THB/tonne depending on product market price

3) The total production cost of cassava chips is 3,300 THB/tonne; 95% of this cost is due to the cost of 2.5 tonne of cassava roots, whereas processing cost makes just 5%.

4) The price of cassava chips ranges 3,700 - 4,000 THB/tonne on the open market, after adding profit margin, taxes, etc. When including transportation cost, the feedstock at plant gate costs 3,900 - 4,200 THB/tonne chips.

5) Conversion rate is 333 litres of ethanol per tonne of cassava chips according to Ngyuen et al. USDA mentions 155 liter of anhydrous ethanol per tonne (USDA 2007), but considering that Cassava is one of the starch-richest crops, we assume that the estimation of Ngyuen et al. is correct.

A detailed breakdown of the feedstock cultivation cost is shown in Figure 5. It demonstrates that fertiliser contributes significantly (i.e 25%) to the overall costs.

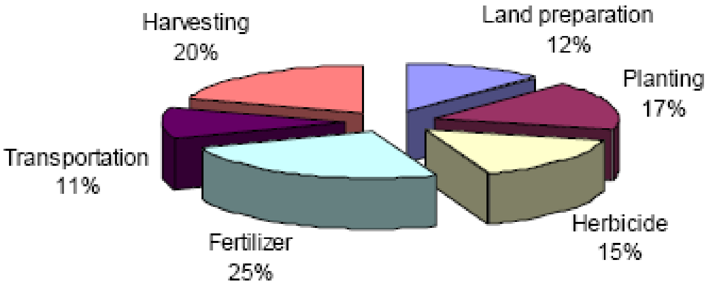

Figure 5 Breakdown of the cassava roots production costs (Nguyen, et al. 2006).

A detailed break-down of the distillery costs is given in Figure 6. The feedstock, including margins, transportation costs and market effects, accounts for 54% of the ethanol production costs.

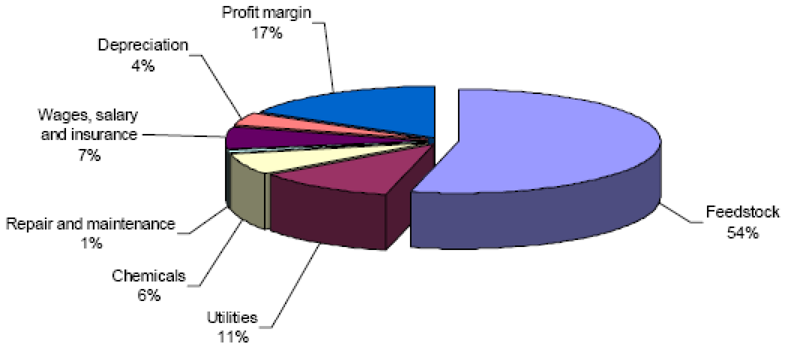

Figure 6 Breakdown of the ethanol production costs (ex distillery) related to a feedstock price of 80.3 □/tonne chips (Nguyen, et al. 2006).

There are several options that slightly improve the economics of the ethanol production from cassava:

- The ethanol conversion produces a sludge residue, which, in principle, is a good soil conditioner and which could be sold to cassava farmers. To realize this option it is

necessary to dewater the sludge, which implies a small additional cost to the distillery.
- Fuel oil, used for heat and electricity generation for the distillery could be replaced by much cheaper rice husk.

These options could decrease the production costs of cassava ethanol by about 5 eurocent/litre.

5.2 Comparison with ethanol from other feedstock

Table 13 shows the production costs of ethanol from other feedstock. Both ethanol from maize in the United States and ethanol from sugar cane in e.g. Brazil can be produced at lower costs than ethanol from cassava, i.e 0.47€/l. However, cassava ethanol has a favourable pricing position in comparison with wheat and sugar beet ethanol in Europe.

Table 13. Ethanol production costs, both calculated and market reported.

	Calculated costs[1] (€/l)	**Market price (€/l)**
Ethanol from sugar beet	0.54	
Ethanol from wheat	0.47	
Ethanol from cassava	0.47	
Ethanol from maize	0.40	0.37 €/l
Ethanol from sugar cane	0.21	0.24 €/l

[1] Hamelinck (2007) calculated the production costs on basis of wheat ethanol in Europe 22 □/GJ_{LHV}, sugar beet ethanol in Europe 26 □/GJ_{LHV}, maize ethanol in USA 19 □/GJ_{LHV} and sugar cane ethanol in Brazil 10 □/GJ_{LHV}. Energy content is 26.4 GJ_{LHV}/tonne, density 791 kg/m^3.

[2] Sugar cane ethanol (FOB Port of Santos) and maize ethanol (US national rack average) market prices August 2007 from ethanolmarket.com.

5.3 Ethanol import to the EU from ACP countries

Generally, ethanol imports to Europe are subject to import tariffs. Depending on the nature of the ethanol, denatured (undrinkable) or undenatured (still drinkable), a low or high tariff is applied. Imports from some countries are subject to a lower or even a zero-tariff. E.g. ethanol imports from the so-called ACP countries (Africa, Caribbean and Pacific Ocean) face no import tariffs (see Table 14).

Table 14. Import tariffs for ethanol.

	Taric code	**Imports erga omnes**	**ACP countries[1]**
Ethanol, undenatured	2207 10 00 10	19.20 EUR / hl	0%
Ethanol, denatured	2207 20 00 10	10.20 EUR / hl	0%

[1] A list of ACP countries can be found at www.europarl.europa.eu/intcoop/acp/

Imports from Brazil are applicable to the all-in import tariff. Depending on the form of the ethanol the costs are increased with 0.102 or 0.192 €/l. Depending on the biofuels regulation in the destination country, it could be necessary to import ethanol in undenaturated form, in order to receive excise exemptions or to count for biofuels obligations.

From table 14 it can be deduced that ethanol imports from ACP countries are favourable. Ethanol produced from cassava in these countries is likely to be sold in Europe at a competitive price.

6 Current status and markets

6.1 Cassava markets and countries

Production

World cassava production amounted 208 million tons in 2005 (FAO, 2007). Since the late 1990's production has grown steadily by 4 to 6%. Nigeria is by far the largest producer of cassava, responsible for 18% of the world production (42 million tons). Second is Brazil with 26 million tons, followed by Indonesia which has passed Thailand as third producer in 2005. In general, over the last years cassava production has mostly increased in Nigeria, Brazil and Mozambique. Production declined mostly in Thailand and China. Figure 7 shows cassava production for selected countries.

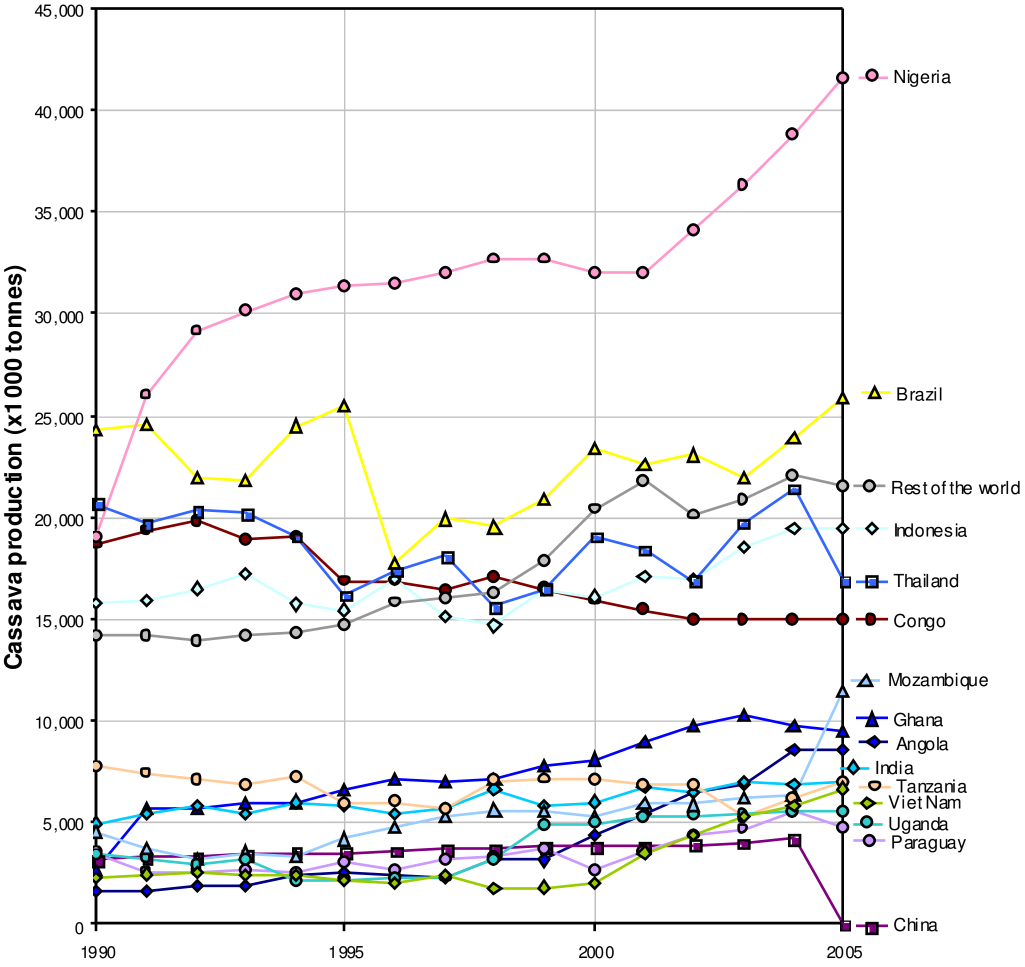

Figure 7 Cassava production in selected countries 1990-2005 (FAO, 2007).

Import and export

Approximately 2% of world cassava production is being traded. Exports have decreased rapidly in the late 1990's and have remained fairly constant since than. Major exporting countries are (in absolute numbers): Thailand, Vietnam and Indonesia. The Netherlands and Germany also export (or rather through-port) significant volumes of cassava (after first having imported it). China is the largest importer (3.3 million tons in 2005), followed by The Netherlands (0.9 million tons). Other European countries have much lower trade volumes. Trade in cassava consists of the following product categories:

- Fresh cassava roots: International trade in fresh cassava roots is mostly confined to transactions between neighbouring countries and is not usually recorded in the official statistics. Some demand exists in developed countries caused by an increasing population that originates from 'cassava producing countries'.
- Dry cassava chips and pellets: Cassava can be chipped or pelletised in order to increase shelf life and to make export available for animal feed uses. The EU is the main market for cassava feed products, as it accounts for about 80% of global imports. The other 20% of trade find their way to China, Indonesia, Japan, the Republic of Korea, the United States, Australia, New Zealand, Malaysia and the Philippines. EU demand for feed cassava products was met mainly by Asian countries, in particular Thailand. Thailand is the most dynamic in meeting the requirements for trade expansion. In recent years, however, falling grain prices following the 1992 CAP reform have decreased demand for cassava feed products in the EU and stalled much of the growth of production in Thailand, where the sector was highly dependent on external markets as its main outlet.
- Starches and flours: Trade in cassava flour and starch, which represents some 15% of overall cassava products trade, expanded in recent years. The major cassava starch and flour importers are, by order of importance, Japan, the Chinese Province of Taiwan, Hong Kong, China, Indonesia, Malaysia, Singapore, the United States and the Philippines.

Cassava pellets have been sold to other destinations at prices much lower than those obtained in the EU. This pattern reflects the export policies implemented by Thailand and Indonesia since the mid-1980s to encourage a diversification of markets. Both countries introduced a "bonus scheme", under which traders were awarded a given amount of the profitable export quota to the EU for each tonne sold elsewhere. Such a scheme encouraged traders to offer very cheap prices to non-EU customers as they endeavoured to increase their entitlements for sale to high-price markets in the EU. As a result, the international cassava pellet market was characterized by a two-tier pricing system that contributed to the expansion of cassava exports to non-EU destinations in the 1980s and early 1990s. (FAO, 2003)

Uses

Worldwide cassava is mostly used for food: 53% of world cassava production was used for food in 2005. Secondly, feed uses amounted to 24%. 22% was used for other purposes. The latter include post-harvest losses and industrial uses. The share of cassava losses was much smaller for Latin America and the Caribbean and for Asia, at 10% and 8% respectively, while it was of the order of 29% in Africa (FAO, 2000). Industrial uses of cassava include utilisation in the manufacturing of paper, cardboard, glues, textile, resins, composite woods, pharmaceuticals and ethanol production. Some large-scale, integrated, cassava starch plants have been reported in Venezuela, whereas in Brazil the scale is generally small. A major constraint of the industry is the unavailability of a regular flow of roots for processing. In Brazil, for instance, cassava starch industries had to stop working for more than four months a year, because of a lack of fresh cassava roots (FAO, 2003).

Table 15. Cassava production and consumption (2005) data for selected countries. Grey shadings indicate countries that have been studied further in detail.

Country *[10^6 tonnes]*	**Production**	**Consumption (food)**	**Import**	**Export**	**Feed and seed**	**Other uses**
Angola	8.6	4.6			1.30	2.7
Belgium			(2004) 0.27	(2004) 0.08	0.16	
Benin	2.9	1.0			0.56	1.3
Brazil	25.9	7.1			13.40	5.2
Cameroon	2.1	1.5			0.16	0.5
China	(2004) 4.2	1.9	3.30		8.80	(2004) 4.4
Colombia		1.6			0.14	0.3
Congo, The	15.0	14.0			0.39	0.6
Costa Rica				0.08		
Côte d'Ivoire	2.2	1.6				0.5
Germany			(2004) 0.03	(2004) 0.13		
Ghana	9.6	4.5			1.40	3.7
Guinea		1.2				0.1
India	7.0	6.5				0.5
Indonesia	19.5	12.0		0.25	0.40	6.5
Italy			(2004) 0.04			
Japan			(2004) 0.03			
Korea, rep. of			(2004) 0.40		0.50	
Madagascar	2.1	1.7				0.3
Malawi	2.1	1.4			0.58	0.1
Malaysia						0.4
Mozambique	11.5	5.1			0.40	6.0
Netherlands			(2004) 0.90	(2004) 0.11	(2004) 1.40	(2004) 0.2
Nigeria	42.6	15.2			11.60	14.8
Paraguay	4.8	0.7			3.90	0.2
Philippines		1.6				0.2
Portugal			(2004) 0.14		(2004) 0.29	
Spain			(2004) 0.81		(2004) 1.73	
Tanzania	7.0	5.2				1.7
Thailand	16.9	8.8		3.0	0.29	(2004) 2.1
Uganda	5.6	3.5			1.40	0.7
U.S.A.			0.07		0.20	
Vietnam	6.6			0.48	2.58	2.0
World	**208.1**	**111.8**	**6.1/3.9**	**6.1/3.9**	**49.9**	**46.3**
Criterion	*>2*	*>1*	*>0.01*	*>0.01*	*>0.10*	*>0.10*

Notes:

a) Differences might occur in summations due to rounding and differences in years (stock levels etc).

b) Most import numbers have been taken for year 2004, since import/export in 2005 was considerably different from previous years due to a large drop of exports in Thailand and Vietnam.

Potential

Table 15 summarises production numbers and cassava uses within the most important cassava growing countries[9]. Based on the cassava production numbers Nigeria, Brazil, Indonesia, Thailand and Congo are definitely the most important countries. These coun-

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[9] Firstly based on annual production (larger than 2 million ton per year), secondly by the height of cassava consumption (> 1 million ton), and finally on volumes of import and export (> 10,000 tonnes), feed and seed use (>100,000 tons) and other uses (> 100,000 tons).

tries inherently have high (food) consumption rates of cassava. By looking at the consumption rate (food consumption divided by production + imports), the relative importance of cassava for food is indicated. From the largest cassava producing countries, Indonesia, Thailand and The Congo have highest food consumption shares; resp. 62%, 52 % and 93%. Lowest shares are observed in Mozambique (45%), Nigeria (36%) and Brazil (28%). Furthermore, the share of 'other uses' is important, mostly because this indicatedsthe share of industrial uses that could become available for ethanol production in the near future. Countries with high shares of other uses are Mozambique (52%), Benin (45%), Ghana (38%), Nigeria (36%) and Indonesia (34%)[10]. The countries which have a large potential for ethanol from cassava, are described in detail in the next paragraphs.

6.2 Status of ethanol production from cassava

No consistent data have been found on production volumes of ethanol from cassava. Some initiatives have been announced and small volumes are being production in mainly Asia (Thailand) and small scale local production in some African countries. In this section the cassava market in relevant countries is described. If applicable, information on ethanol production is provided. It appears that currently approximately 100 kton of cassava ethanol is being produced. In the short term this could increase up to 2000 kton if large production facilities in Thailand and China start operating and if Nigeria implements its ambitious plans for future ethanol production. This informationis based on information publicly available on the internet. At the end of this section the potential cassava ethanol production is calculated.

Table 16 Key information on cassava growing countries.

Country	Cassava yield [ton /ha]		Cassava price [USD/ton]		Ethanol production [kton/year]	
	2004	2005	2004	2005	Production	Announced/planned
Benin	13.0	12.9	n.a.	n.a.		*n.a.*
Brazil	13.6	13.6	22	27		*Initiatives*
China	16.8	19.6	547	547		*310 kton announced*
Congo	9.7	9.4	76	68		*Initiatives*
Ghana	12.4	12.8	90	93		*10 kton*
Indonesia	15.5	15.9	75	83		*50 kton announced*
Mozambique	6	10.4	107	113		*Initiatives*
Nigeria	11	11	439	548		*450 kton planned*
Thailand	20.3	17.2	22	34	*23 kton,*	*1000 kton announced*

Cassava prices are quoted from the FAO database, indicating the producers price in US$ per tonne fresh or dried cassava. Large differences in cassava prices have been observed. Especially China and Nigeria show high prices, even if all prices are corrected for purchasing power according to the PPP (purchasing power parity). This could be caused by

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[10] The uncertainties in data for small producing countries have to be taken into account as well.

differences in the definition of cassava (fresh or dried, the latter probably having a premium price). Time was too limited to identify the reasons behind the differences.

The following countries have been identified as having a high potential for future cassava based ethanol production. As stated before, no large scale cassava ethanol production is currently existing, but countries having high shares of industrial cassava use and relative low feed use have been studied in detail. Countries which have ethanol initiatives or ambitious governmental plans, have also been included.

- *Benin*

Between 1996 and 2003, cassava production doubled to reach a total output of 2.9 million tonnes, while the per-ha yield increased by 25%. This strong performance was largely the result of the government scheme “a billion for cassava” which offered credits, fertiliser and cuttings of improved varieties to producers to encourage them to increase production. However, not much was done to improve marketing at the same time (The Bahama Journal, 2007).

- *Brazil*

Cassava is grown in the regions of Sao Paulo (6%), Mata Grosso do Sul (17%), Parana (75%) and Goias (2%). These regions are also know for their large sugarcane and ethanol production. Cassava is mostly used for starch production; 36% is cassava derived starch. However, corn is still the most important feedstock for starch production (63.8%) (Henry and Cardoso, 2003). In Brazil cassava is currently not being used for ethanol production. Negative experiences with cassava in Brazil have been quoted by FAS: Large-scale farming of cassava failed because of pests and diseases and manual harvesting appeared very labour intensive and time consuming. High ethanol demand could increase interest in cassava as possible feedstock. However, this seems unlikely due to the fact that Brazil is mainly focussing on sugarcane and there appears to be no need for alternative feedstocks (besides soy for biodiesel).

- *China*

China’s current cassava production is estimated at 7.5 million tons per year. Increasing land area planted to cassava (it can grow on marginal land) and technological advances could eventually add 21 million tons to cassava production. In the meantime, cassava imports from Thailand, Vietnam, and Indonesia are surging, up from 257,000 tons in 2000 to more than 3.3 million tons in 2005. Semi-tropical Guangxi region offers an ideal mix of climate and soil conditions for growing cassava (FAS/China, 2006).

A subsidiary of China National Cereals, Oils & Foodstuffs Corporation recently reached a deal with the government of southern Guangxi Zhuang Autonomous Region to construct a 200,000-ton cassava ethanol plant in the capital Nanning. The Nanning plant, the first phase of the project, will be finished by mid-2007. Another ethanol plant in southern China, which is a joint venture of the provincial and national governments, will open in October 2007 with production capacity of 110,000 tons of ethanol per year. With cassava as the main input, the plant is expected to supply much of southern China when it reaches production of 1 million tons per year in 2010 (Worldwatch Institute, 2007).

- *Congo*

Cassava is a very important food crop in Congo, with 93% of total production being used for food consumption. Also the leaves are used as a vegetable. As of October 2007, Brazil has signed two agreements to help Congo with training, technology and financing to produce ethanol (Reuters). Drawbacks for small scale cassava/ethanol production in Congo are the civil stability, poor road access and the existence of import subsidies on rice and wheat.

- *Ghana*

In Ghana, the cassava transformation has lagged behind Nigeria by about a decade. For example, the dramatic increase in cassava production occurred in Nigeria from 1984 to 1992 and in Ghana from 1990 to 2001. In Ghana, until the drought which occurred in the early 1980s and resulted in the failure of most food crops except cassava, government agricultural policies emphasized on stimulating large scale production of grains by the public sector and neglected cassava as an inferior food whose consumption was destined to decline as incomes increased.

Caltech Ventures Ghana Limited, a biofuel company founded by members of the Ghanese diaspora, will begin the production of ethanol from cassava at Hodzo, near the city of Ho, in 2007 when its $6.5 million production plant will be ready. The company's total investment in the venture is $10 million. Caltech Ventures Ghana Limited has established a 162 hectare cassava seed plantation with plans to expand it to 486 hectares next year. 60 percent of the six million litres of ethanol to be produced yearly will be exported. It has also organised a corps of cassava out-growers to provide the needed raw material for take-off. The project has the potential to provide 600 jobs, when its ethanol plant comes to full production (Biopact 2007).

- *Indonesia*

Relative small amounts of Indonesia's cassava production are used for food consumption. In Indonesia two ethanol plants are currently operating, both using molasses as raw material. The industry is also looking at cassava as a feedstock. Since molasses is also used to produce monosodium glutamate, cassava may be an attractive alternative. At least two companies are currently making plans to use cassava as an feedstock (FAS/Indonesia, 2007). Indonesia's largest-listed energy firm, PT Medco Energi Internasional, plans to spend $135-$144 million on three ethanol plants. Each ethanol plant needing an investment of $45 million. One plant in Sumatra's Lampung will have a capacity of 60 million litres of cassava-based ethanol a year, which is going to be exported to India, Korea, Taiwan and China (Reuters).

- *Mozambique*

Compared to other African countries Mozambique uses only 45% of the cassava supply for food consumption, whereas 52% is being used for other purposes. Recently, a panel of scientists has put efforts in the development of using cassava for ethanol production. A cassava-based ethanol industry will be adding value to the crop and provide major opportunities for poverty reduction amongst the country's small subsistence farmers. The Mozambique Bio-Fuels Industries is also promoting the use of cassava (and jatropha) for biofuel production (Biopact, 2007).

- *Nigeria*

Yields were boosted when high yielding 'TMS' varieties were introduced and supported by the government. In 2002, cassava suddenly gained national prominence following the pronouncement of a Presidential Initiative. The intent of the initiative was to use cassava as the engine of growth in Nigeria. To put Nigeria in the global context for competition the country needs to upgrade the use of cassava into primary industries such as starch, ethanol, chips and flour in order to provide an industrial base for further diversification of its national economy (Knowledge for Development, 2007). This initiative aimed to produce 107 million tons of cassava in 2007 with 78% destinated for export. The majority of cassava will be used for animal feed (85%) and 3% will be dedicated for ethanol production (FAO, 2004). Highest potential for future increased cassava production and processing facilities is in the southwest of Nigeria. FAO (2004) has made the following recommendations in order to enable Nigeria to exploit its large cassava potential. The cassava industry throughout Nigeria has long been neglected as a valued and respected contributor to modern agriculture. Yet cassava production is greater than the 'more respected' and 'more organized' agricultural commodities in Nigeria. For the cassava industry to mature in Nigeria it must organize itself. Competitive funding in support of excellence and innovation within the cassava industry should be given priority.

In 1994, NIYAMCO (Nigerian Yeast and Alcohol Manufacturing Company) began looking for an alternative source of raw material. Dried cassava chips was selected as a suitable raw material for the production of ethanol. The production facility of NIYAMCO required about 30 tons of dried cassava roots per day. Because of problems in organizing the collection of dried cassava chips from scattered smallholders, NIYAMCO had to close its ethanol plant. If the 88 million liters of alcohol currently imported each year for the liquor industry were produced with cassava roots in Nigeria, it would open up a market for about 600,000 tons of cassava roots, or about two percent of national cassava production (Nweke, 2003).

- *Thailand*

Production and export of cassava has dropped significantly in 2005, whereas more cassava was used for food production. Most cassava in Thailand was exported as cassava chips and pellets to Europe, to be used in the animal feeding industry. During the late 1980s, Thailand's cassava-production area covered 1.6 million ha. Almost all of this was destined for the lucrative export market for cassava pellets in Europe. However, changes in the EU's agricultural policies in 1993 lowered the support price of their own grain crops, and made Thailand's cassava pellets no longer competitive as a cheap source of animal-feed. Thus, the amount of cassava pellets Thailand exported to the EU began to drop. Foreseeing the problem of overproduction, the Thai government tried to decrease the cassava-growing area by encouraging farmers to plant other crops. However, none of these were as well adapted to the climatic conditions in the Northeast as cassava. As a result, farmers continued to grow cassava, albeit on a reduced area of about 1 million ha. While the area was reduced, cassava yields started to increase substantially from about 14t/ha in 1995 to 22t/ha in 2006/2007. The result was that total cassava production decreased only marginally from a peak of 24 million tons in 1989 to about 16 million tons in 1998/1999 and back up to 25 million tons in 2006/2007. The Thai cassava industry changed from making mainly cassava pellets for export to making more and more cassava starch for both the domestic and export markets. Currently, cassava starch and modified starch industry absorbs over 50% of all cassava roots produced in the country. Chinese neighbours to the north have also built more and more starch factories, to the point that domestic production could not keep up with demand. Thus, in 2001, they started importing dry cassava chips from Thailand, firstly in very modest amounts, but increasing every year to four million tonnes in 2006.

Presently there is only one ethanol factory in the country using cassava as its raw material and producing about 80,000 litres per day. However, two additional factories are ready to start operation and another 12 factories should be completed by the end of 2008, producing a total of 3.4 million litres of ethanol per day. This will require an additional six million tons of fresh roots, on top of the 25 million tons currently being produced. Since the cassava growing area cannot increase substantially due to competition from other crops, the increased supply can only be met through increases in yield (Biopact, 2007).

In Thailand, ethanol production from cassava will not necessarily cause an over-demand to the existing cassava industries, since the starch industry is not expected to grow much further and the pellets industry will decline somewhat. At an annual production of 20 million tonnes of fresh roots in 2005, there was 4 million tonnes of roots available as a surplus to the feed industry and to make ethanol from. The Thai agricultural policy strives to increase yields without increasing the area planted with cassava (which is now restricted to 1 million ha). Due to continuous research and development on cassava variety improvement and cropping efficiency, Thailand has been able to increase cassava yields from 13 tonnes/ha in 1995 to an average of 17.2 tons/ha in 2005.

6.3 Potential volumes of cassava ethanol

The potential of cassava ethanol can be estimated by taking the production share of ‘other uses’ in a selected country. Within the category “other uses” a large share is used for industrial purposes. Industrial parties may have to compete with future ethanol production. This avoids direct competition with cassava used in food and feed (see next chapter on sustainability). Table 17 summarises the cassava-ethanol production potential for various countries. It appears that in total 6.6 million tonnes of ethanol can be produced from cassava annually. This represents a share of 16% in current world fuel ethanol production. Nigeria and Indonesia show the largest potential of cassava ethanol production, which is e.g. reflected in the ambitious ethanol policy plans in Nigeria. Also in Indonesia, several initiatives have been identified and three ethanol plants have been announced. Thailand shows a smaller potential, due to the large volume of cassava chip exports.

Table 17 Top-10 cassava ethanol potential (based on cassava available for 'other uses')

Country	**Cassava used for 'other uses' [million ton / year]**	**Potential cassava ethanol production [kton / year]***
Benin	1.3	185
Brazil	5.2	739
China	4.4	625
Congo, The	0.6	85
Ghana	3.7	525
Indonesia	6.5	923
Mozambique	6.0	852
Nigeria	14.8	2,102
Thailand	2.1	298
World	(17%) 46.3	6,576

**Assuming that from 1 ton of fresh cassava 180 litres ethanol can be produced; And ethanol density : 0.789 kg/l.*

7 Sustainability issues

7.1 Competition between food and ethanol

Cassava is a staple food for 500 million people in the humid tropics. Thus, cassava price increases caused by a rising cassava demand for ethanol production are likely to have effects on the food access of poor people which do not produce cassava themselves.

However, cassava price increase on the existing cassava market are not to be expected, if:

- The demand for cassava within other industry sectors (e.g. the fodder market) is diminishing by the same volume needed for ethanol production. To our knowledge, however, there are no indications that such a development is currently taking place or is to be expected in the near future.
- According to Horizonte (2003) a substantial proportion of the cassava harvest in tropical regions is lost. By using heat produced out of cassava residues, cassava losses can be reduced considerably. Thus, using improved conservation processes could make cassava available for ethanol production that would have been lost otherwise.
- The increasing demand for ethanol production is covered exclusively by cassava which has been produced in addition to the current cassava production. This can be achieved without severe negative ecological consequences by increasing the yields of existing plantations using sustainable production methods or by setting up new cassava plantations on "idle" land (see textbox). Cassava could be especially appropriate for the cultivation on idle lands, as these lands often do not have the best soil qualities and cassava still has reasonable yield on land where other crops cannot be produced.

Doing so, a new market for cassava from additional production is set up. The increasing demand from the ethanol industry will only become effective on this market. Thus, the existing market for cassava will not be influenced by the increasing cassava demand of the ethanol industry. However, if the cassava demand for the food sector would increase in the future, additional cassava will have to be supplied by the new ethanol market for cassava from additional production.

Textbox: Idle land
Several authors have indicated the large potential of energy crops on degraded land. The challenge with realising production on idle land is that there is no internationally agreed definition of "idle land". Not having clarity about which land can be considered to be 'idle' forms a major barrier to realising production on idle land. Therefore it is advised that stakeholders (market players, NGO's, governments) set up a programme to identify areas which can be classified as idle land. Such a programme should build upon existing knowledge to protect biodiversity such as in the Convention on Biological Diversity.

Furthermore, such a programme should include active consultations with:
- local and national governments of the relevant areas;
- biodiversity experts with relevant local experience;
- local communities (assisted by NGO's with local representation);
- industry representatives.

Guidelines for designating land as idle land are given below. Idle land for sustainable biomass production should meet the following conditions:
- Compliance with the criteria of the RTFO Sustainable Biomass Meta-Standard (a biofuel certification system which is currently being set up in the UK) on carbon stock conservation.
- Compliance with all criteria of the RTFO Sustainable Biomass Meta-Standard on Biodiversity, i.e. no conversion in or near areas with one or more High Conservation Values.
- Compliance with all criteria of the RTFO Sustainable Biomass Meta-Standard on land rights and community relations).
- In a reference year (e.g. 30-11-2005), the land was not used for any other significant productive function, unless a viable aternative for this function existed and has been applied which does not cause land-use change which is in violation with any of these criteria for "idle land".

The criteria on biodiversity refer to High Conservation Values, a concept introduced by the Forest Stewardship Council. Guidelines have already been drafted and applied on how to identify such High Conservation Values. It could be an interesting option to expand the process of identifying High Conservation Values to also include the identification of idle land.

To improve the food access of people in regions where cassava for ethanol production is cultivated according to the criteria of additional production described above, it would be possible to either intercrop other food crops on biofuel plantations or to sell a part of the produced additional cassava supply to the food market.

7.2 Ecological and social sustainability aspects

At least the following ecological and social aspects have to be considered to assess the sustainability of producing feedstock for the biofuel industry, no matter what agricultural crop is used:

Ecological Criteria

1. Carbon storage: Carbon losses can be caused by the conversion of high carbon storage land (e.g. forests) into biofuel plantations.

2. Biodiversity: Biodiversity losses can be caused by the conversion of high carbon storage land (e.g. forests) into biofuel plantations.

3. Soil quality: The soil quality of biofuel plantations may decrease, e.g. in the case that no measures are taken to prevent erosion, an excess application of pesticides and

fertilizers (an overuse of nitrogen decreases the cassava crop quality for food consumption as well) and a decrease of soil fertility due to an excessive export of nutrients (especially potassium in the case of cassava)

4. Water use: The water quality in the production regions might deteriorate in the case of an overuse of pesticides and fertilizers. A sustainable water use has to take the natural ground water level regeneration rates into account.

5. Air quality: The air quality in the production regions might deteriorate in the case of burning of residues or the use of fires to burn forest with the aim of setting up new biofuel plantations

Social Criteria

6. Labour conditions: Proper labour conditions on the biofuel plantations include e.g. the prohibition of child labour and forced labour as well as the workers right to organize themselves.

7. Land rights: Taking existing land rights into account is especially problematic in countries where companies set up large scale biofuel crop plantations and do not comply with the existing legislation.

Currently, a number of European countries (United Kingdom, The Netherlands and Germany) and the European Commission are setting up certifications systems to assure a sustainable production of biofuels. These certification systems are mostly based on existing, voluntary certification system for different agricultural crops and forest products. However, there is currently no certification system for cassava production in place.

Sustainable cassava production for the ethanol industry may be guaranteed by setting up a sustainability certification system for cassava. In addition to the ecological and social sustainability criteria mentioned above, it is recommended to add a criterion on “additional production” in the certification system. Thus, increasing prices on the existing market for cassava could be prevented. Doing so, the displacement of current agricultural production with possible negative ecological consequences could be prevented as well.

Although certification would be desirable also for the cassava food market from an ecological point of view, it is not recommended to include the food sector in the certification system, as the costs of certification would be imposed on the users of cassava food who often have a very low income.

8 Conclusions

1. About 54% of the world's cassava is produced in Africa, 29% in Asia and only 14% in Latin America (FAO, 2007).
2. Growing and harvesting cassava is a manually intensive activity and thus lends itself to small scale production units.
3. Post harvesting activities are not very capital intensive either and can therefore be conducted at the farm level.
4. Other activities in the supply chain (e.g. refining, extracting, marketing and packaging) tend to be more capital and knowledge intensive and thus benefit from economies of scale.
5. The supply chain provides possibilities for small-scale farmers on marginal lands to become involved in producing a cash crop.
6. According to TIPS (2007), on the long-term, cassava best potential growth market is its application in starch and starch-based products.
7. Countries that have the greatest potential for future ethanol production are countries such as Thailand, Nigeria and Ghana, which produce cassava for higher value added products, such as for animal feed or for industrial starch production. This avoids a direct competition with food uses of cassava.
8. Possible drawbacks could be the limitations of Thai exports, and political instability in Nigeria and Ghana.
9. The worldwide growth in ethanol production has resulted in increased awareness ofthe possibilities of African cassava.
10. More developed countries such as Thailand have made the step towards higher added value uses of cassava in the past and have become leading exporter of cassava chips and pellets. This development could very well indicate the future direction of selected African countries.
11. Cassava could be especially be appropriate for the cultivation on idle lands, as these land often do not have the best soil qualities and cassava still has reasonable yield on land where other crops cannot be produced.
12. Large opportunities exist for cassava ethanol production. Due to its high availability, its large potential to optimise yields and due to its integration in small scale communities, ethanol can be produced in a viable way.
13. Drawbacks may result from the competitive pressure that co-markets of ethanol, such as the starch market, could exercise.
14. Also, the application of cassava in African animal feed market could potentially interfere with large scale ethanol production.
15. The current development of sustainability criteria will most likely also be extended to cassava ethanol.

16. To avoid food or fuel debates, it has to be assured that additional cassava is grown for ethanol, preferably on idle land. This enhancess cassava's potential, due to its cultivation potential on low fertility soils.
17. Beneficial export conditions and relative low production costs will enhance cassava's potential.
18. In order to develop a market and infrastructure for cassava the following aspects should be addressed:
    - Increase stable cassava yields. Use high yielding root material and optimise harvesting methods in order to make large volumes of additional cassava available.
    - Explore the possibilities for integrating small scale ethanol production facilities with opportunities for biogas production.
    - Define domestic ethanol markets and possibilities for exporting ethanol.
    - Address sustainability issues from the start.

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