Energy Sorghum

An alternative energy crop

A Handbook

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The SWEETFUEL project

The SWEETFUEL project objectives are to breed for improved varieties and hybrids of sorghum for temperate, tropical semi-arid and tropical acid-soil environments by pyramiding in various combinations, depending on region and ideotype, tolerance to cold, drought and acid (Al-toxic) soils, high production of stalk sugars, and easily digestible biomass and grain. During the project, molecular genetic and physiological breeding support is given and agro-ecological adaptation and sustainable practices are developed. Integrated technology and impact assessments are also included. Project outcomes will be new germplasm, sustainable practices and commodity chain concepts adapted to each target region. SWEETFUEL research involves structured participation of stakeholders, including policy makers.

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1. Introduction

Increasing world market prices for fossil fuels, driven by limited reserves, growing demand and instability in producing regions, now render renewable fuels economical. Such fuels are also a pathway to reducing greenhouse gas (GHG) emissions and mitigating climate change. The transport sector which is almost totally dependent on fossil fuels, particularly for powering personal vehicles and trucks, is the most concerned sector. Biofuels, defined as solid, liquid or gas fuels derived from biomass, are today the only direct substitute for fossil fuels on a significant scale particularly in transport sector. Biofuels are considered environmentally friendly because the CO_2 emissions they produce during combustion is balanced by the CO_2 absorbed by the plants growth. To be a viable substitute for fossil fuels, an alternative fuel should not only have superior environmental benefits over the fossil fuels it substitutes, be economically competitive with it, and be available in sufficient quantities to make meaningful impact on energy demand, but it should also provide a net energy gain over the energy invested to produce it and have minimal effect on food security.

Bioethanol is one type of liquid biofuel resulting from the fermentation of sugars. Whether bioethanol represents a viable alternative to fossil fuels depends on the raw material and location of production. Production from sugarcane in Brazil has a positive energy balance and allows large GHG savings, but production from corn in the USA results in less positive if not sometimes negative balances.

Sorghum (*Sorghum bicolor* L. Moench) is one of the most efficient crops to convert atmospheric CO_2 into sugars. Depending on the cultivation even it may have advantages compared to sugarcane in the tropics and corn in the temperate zone, making it a promising crop for bioenergy while meeting food and fodder needs. Among the different crops that have been envisaged to produce ethanol, sorghum seems to have a great untapped potential. Sorghum is a good multipurpose crop for simultaneous production of (i) grain from its panicle as food, (ii) sugary juice from its stalk for making syrup, jaggery or ethanol and (iii) bagasse and green foliage which can be used as an excellent fodder for animals, for gasification, for second generation bioethanol production, as organic fertiliser, for paper manufacturing or for co-generation. Moreover, sorghum is a C4 plant with many potential advantages, including high water, nitrogen and radiation use efficiency, broad agro-ecological adaptation as well as a rich genetic diversity for useful traits. For developing countries sorghum provides opportunities for the simultaneous production of food and bioenergy, thereby contributing to improved food security as well as increased access to affordable and renewable energy sources. In temperate regions (e.g. in Europe) sorghum is seen as a promising crop for the production of raw material for 2nd generation bioethanol.

Unlike sugarcane and corn, sorghum has little breeding history and the potential of production improvement through genetic enhancement is thus very high. In order to exploit the advantages of sorghum as potential energy crop for bioethanol production, the project SWEETFUEL (Sweet Sorghum: An alternative energy crop) has been launched. This project is supported by the European Commission in the 7th Framework Programme. Thereby, the main objective of SWEETFUEL is to optimise yields by genetic enhancement and improvement of cultural and harvest practices in temperate, tropical semi-arid and tropical acid-soil environments. The aim of this Handbook is to serve as a reference for sorghum cultivation, primarily for bioenergy production.

2. Characteristics of sorghum

2.1. History of sorghum use

Sorghum is one of the oldest cultivated crops in the history. It is believed that it originated from Africa. Wide varieties in the genus sorghum were observed in the north Eastern regions of Africa comprising of Ethiopia and Sudan in Eastern Africa (Doggett 1988).

During the first millennium BC, sorghum was probably carried from eastern Africa to India in ships as food by the chow traffic which operated for about 3,000 years between east Africa and India via the Sebaean Lane in Southern Arabia. This crop might have been spread along the coast of Southeast Asia around China in the beginning of Christian era. However, a possibility that cannot be denied is that sorghum might have arrived much earlier in China by the silk trade routes. Around 200 AD or even earlier sorghum made its way into Eastern Africa from Ethiopia via the local tribes, who cultivated this crop mainly for grain and the sweet cane was chewed for pleasure and nutrition. Later, the Bantu tribe carried this crop with them to the Savannnah regions of Western and southern Africa who used the grain mainly for making beer. The Bantu tribe later moved this crop during their expansion from southern Cameroon region around first century AD, and the southern border of the Congo forest belt (FAO 1995). Sorghum was introduced in the Caribbean islands and other Latin American countries from West Africa through the slave trade and by navigators plying the Europe-Africa-Latin America trade route in the early 17th century (Srinivasa Rao and Kumar 2013).

The earliest cultivar 'China Amber' of sorghum was introduced from Shanghai, China to France in 1851 by Mr. Montigny, consulate of France in Shanghai (Henri 1864). Then from France to USA in 1853 by William Prince, a New York nursery man who received seeds from France (Srinivasa Rao and Kumar 2013). In the USA sorghum was used as a sugar crop to produce syrup. Several groups attempted to produce granulated sugar from sorghum juice but discovered that the fructose and glucose in the juice interferes with the crystallisation of the sucrose. Concentrating the sugar into syrup was found to be the easiest way to make a stable product for consumption and sales.

Because of the rapid increase in crude oil prices that occurred during the 1970s, sorghum has been investigated as a potential source of fermentable sugars for ethanol fuel production due to the crop's high sugar content and biomass production, wide geographic and climatic adaptation, and relatively lower water and fertiliser requirements. In many countries, research funding has increased for 'green' alternative fuels due to public concern for possible climate change from carbon dioxide produced by burning fossil fuels and depletion of the world supply of petroleum.

Sweet sorghum is similar to grain sorghum but accumulates high amounts of sugar in the stems that can be used for a variety of uses such as food, fodder, fuel and fibre befitting the sobriquet 'SMART CROP' (Kumar *et al*. 2010).

Sweet sorghum is also valued for the production of commercial products such as alcohol (potable and industrial grade), syrups (natural and high fructose), glucose (liquid and powder), modified starches, maltodextrins, jaggery, sorbitol and citric acid (downstream products from starch) (CFC-ICRISAT 2004). In addition, due to its fibre content sweet sorghum can be used for bedding, roofing, fencing and paper manufacturing.

2.2. Botanical classification of sorghum

Sorghum is classified as follows:

Division: Magnoliophyta
Class: Liliopsida
Subclass: Commelinidae
Order: Cyperales
Family: Poaceae
Subfamily: Panicoideae
Tribe: Andropogoneae
Subtribe: Sorghinae
Genus: Sorghum *bicolor*

The genus *S. bicolor* represents all annual cultivated, wild, and weedy sorghums along with two rhizomatous taxa: *S. halepense* and *S. propinquum. S. bicolor* was further broken down into three subspecies: *S. bicolor* subsp. *bicolor*, *S. bicolor* subsp. *drummondii*, and *S. bicolor* subsp. *verticilliflorum*. Cultivated sorghums are classified as *S. bicolor* subsp. *bicolor* (Harlan and de Wet 1972). House (1985) described further the five different major races: *bicolor, caudatum, durra, guinea,* and *kafir*. The correct name for the cultivated sorghum which is currently in use was proposed by Clayton (1961) and is *Sorghum bicolor* L. Moench.

All sorghums identified botanically as *Sorghum bicolor* subsp. *bicolor* have 2n = 20 chromosomes. Commercial cultivars of *Sorghum bicolor* (L.) Moench are categorised into the following agronomic variants: grain sorghum, forage (or fodder) sorghum, fiber sorghum, broom sorghum, sweet sorghum and biomass sorghum. The agronomic orientation of the variety depends on its phenotypic characteristics.

- Grain sorghums: Sorghum cultivars with high grain yield established as food and feed crop
- Fibre sorghums: Sorghum cultivars with a high content of fibre; potentially used as fibre or energy crop
- Broom sorghums: Sorghum cultivars that exhibit inflorescences with long and elastic branches, mainly used for brooms
- Sweet sorghums: Sorghum cultivars with juicy stems and high juice sugar content in their stalks, potentially used as an energy and/or food crop
- Biomass sorghums: Sorghum cultivars with high lingo-cellulosic biomass yield, potentially used as energy crop

In this book and in reference to the SWEETFUEL project, the term energy sorghum will be used to refer to both sweet sorghum and biomass sorghum.

2.3. Morphology

The different botanical parts of the sorghum plant are schematised in Figure 1.

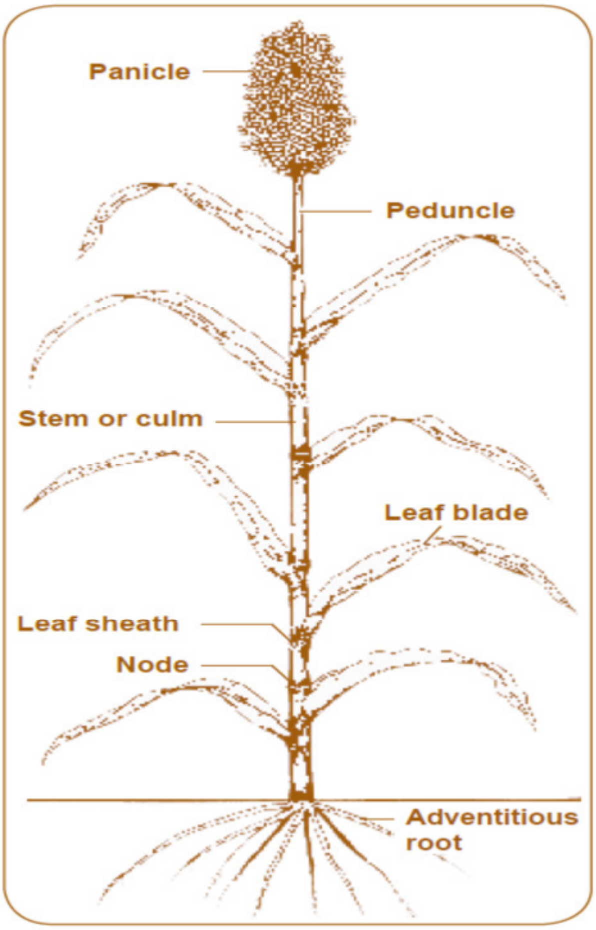


Figure 1: Botanical parts of a sorghum plant (Murty *et al.* 1994)

2.3.1. Seeds

Sorghum is an annual plant that grows from seeds. Panicles of sorghum can produce up to 4,000 starch containing seeds. The seed is composed of three parts: pericarp, albumen and embryo. It is spherical in shape but somewhat flat on one side. They vary in size (weight of 1,000 seeds varies from 6 to 85 g) and in colour from red, brown, white to black (Figure 2).

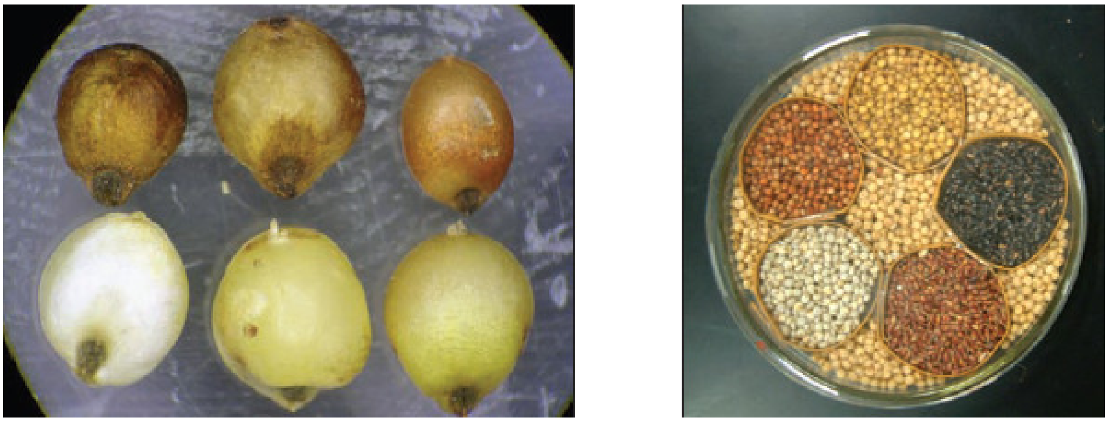


Figure 2: Different varieties of sorghum seeds showing variability in shape and colour (Reddy *et al.* 2008)

2.3.2. Roots

The sorghum root system consists of 3 types of roots: Primary roots, secondary or adventitious roots and brace or buttress roots. Primary roots develop from the radicle and die subsequently. After senescence of primary roots, adventitious roots develop from underground nodes and can extend up to 2 m. Adventitious roots are small and uniform. These roots mainly supply nutrients to the plant. Brace roots develop from the root primordia of the basal nodes above the ground level (Figure 3). They are stunted, thick, and above ground level. These roots provide anchorage to the plant.

Figure 3: Brace or buttress roots of sorghum (© Braconnier)

2.3.3. Stalk and peduncle

Sorghum develops a main stem (stalk) with secondary tillers growing from the collar. The number of tillers depends on variety and cultural conditions. The stem of sorghum consists of alternating nodes and internodes, each node supporting one leaf. The diameter of the stem ranges from 0.5 to 5 cm in diameter near the base while the height at maturity varies between 0.5 to 5 m depending on the variety and the environmental conditions.

Peduncle is the top internode that supports inflorescence. Its growth is independent from the rest of the plant. It is usually straight, except for the dura race where peduncle is arcuated. Its length depends on variety and environmental conditions.

2.3.4. Leaves

According to cultivar and environmental conditions, leaves number varies from few units up to 30. They are composed of a long sheath that embraces the stalk and a blade whose length is from 30 to 135 cm and width from 1.3 to 15 cm. Sorghum leaves are typically green, glasslike and flat, and not as broad as corn leaves. The leaf blades of young leaves are upright but the blades tend to bend downwards as leaves mature. Stomata occur on both surfaces of the leaf. A unique characteristic of sorghum leaves is the rows of motor cells along the midrib on the upper surface of the leaf. These cells can roll up leaves rapidly during moisture stress.

2.3.5. Inflorescence

The flowering structure or inflorescence (Figure 4) in sorghum is called panicle or head. The panicle is a compound raceme type (a branched cluster of flowers in which the branches are racemes). Each raceme consists of one or several spikelets. The panicle may be short, compact, loose or open, composed of a central axis that bears whorls of primary branches on every node. The racemes vary in length according to the number of nodes and the length of the internodes. Each primary branch bears secondary branches, which in turn bear spikelets. The central axis of the panicle, the rachis, is completely hidden by the density of the panicle branches in some, while it is completely exposed in others. The spikelets are usually in pairs on the branches, one being sessile and fertile and the second borne on a short pedicel and male or sterile.

Figure 4: Inflorescence of sorghum (left: © Braconnier, right: © Rutz)

2.4. Growth stages

Growth stages of sorghum start by germination and ends in the physiological maturity stage. The duration of these growth stages may vary with planting date, genotype and location (latitude).

Germination: At optimum temperature (25℃ to 30℃) and moisture, the sorghum seed germinates in 3 to 4 days. When a sorghum seed is sown in a moist soil, the seed swells due to moisture absorption. The seed coat breaks a small shoot (coleoptile) and a primary root (radicle) emerges. If temperatures are cooler, emergence may require 1 to 2 weeks.

Emergence: Initially the young seedlings take nutrients from the endosperm of the seed. The coleoptile emerges from the ground and the first leaf breaks through the tip. The mesocotyle grows during this period and a node is formed at the base of the coleoptile just below ground level. During that period, root growth is quite active with the emission of seminal root then adventitious roots with a high speed growth.

Vegetative stage: After emergence, the vegetative growth is intensive with the production of leaves, nodes, internodes, roots and for some cultivars tillers (after about 15 days). The optimum temperature for vegetative growth is 33-34℃. During this time until flowering, the plant grows rapidly. It produces much of the leaf area, which will be important during the grain-filling period. At this time, the head develops and the stalk grows rapidly. Growth that occurs after flowering result only from cell extension.

Boot stage and emergence: Before inflorescence appears, sheath of the flag leaf swell and in 6 to 10 days the peduncle grows rapidly, pushing the head out of the flag leaf sheath allowing panicle emergence and development. At flowering, between 60 and 70% of the total nutrient uptake already would have occurred.

Flowering: 2 to 5 days after the emergence of the inflorescence from the boot, the flowers begin to open. This phase corresponds to a deeply change of the plant physiology. The flowering can be observed from the yellow pollen from the anthers on the panicle. It takes about 6 days for the whole inflorescence to complete flowering. Sorghum is considered as an autogamous plant even if the allogamy rate can reach 30% in few varieties. Viability of pollen is short, 2 to 4 hours while period of stigma receptivity is much longer, several days.

Physiological maturity: The final stage of growth, from flowering to physiological maturity, is the important grain-filling period. It can take from 30 to 50 days depending on the variety and the environmental conditions. During this time, most of carbohydrates synthetized by the plant goes into the grain. Parts of the reserves stored in the stalk are being moved into the grain, and the plant is taking up approximately the final one-third of the nutrients. If drought occurs, both uptake and grain filling may be limited. This physiological maturity is not harvest maturity. At physiological maturity, the grain moisture will be 25 to 40%, and it must dry considerably before it can be harvested and placed in conventional storage. For high moisture grain or early harvest and artificial drying, sorghum can be harvested at any time after physiological maturity. Physiological maturity can be determined by the dark spot on the seed at its insertion. The cultivated sorghums mature in 100 to 140 days depending on the variety and planting date.

2.5. Overview on properties

Sorghum is a C4 plant that has very interesting characteristics: (i) its growth cycle is short (about four months), (ii) the crop can grow and develop from a seed, (iii) its production can be completely mechanised, (iv) sweet cultivars produce sugar in the stalk, and starch in the grains, (v) it has a high water and nutrient use efficiency, (vi) the bagasse produced from sorghum has high biological value when used as forage and good combustion when used for cogeneration and (vii) it has a wide adaptability to the environment.

2.5.1. Genetic diversity for useful traits

The genus *Sorghum* comprises a high genetic diversity (Assar *et al*. 2005; Uptmoor *et al*. 2003), and therefore, there is potential for crop improvement and increased productivity. Diversity of colour and shape shows the enormous amount of genetic variation in *Sorghum* species (Figure 5). Cultivated sorghums can be divided into three main categories based on end product utilisation: grain sorghum for grain production, sweet sorghum for sugar and/or grain production and biomass sorghum for biomass production. There are virtually no biological or taxonomical barriers or boundaries among these cultivated forms for hybridisation, and they all belong to the same species.

Figure 5: Diversity in colour and shape of panicles showing the enormous amount of genetic variation in *Sorghum* species (© Braconnier)

Early domestication of sorghum was associated with changing the small-seeded, shattering open panicles to larger, non-shattering seeds and more compact panicles (Dhillon *et al*. 2006). Recently, plant breeders focus on improving sorghum to serve as food, feed, fuel (Laopaiboon *et al*. 2007; Tarpley and Vietor 2007; Vermerris *et al*., 2007) depending on the local needs of the country (Figure 6). This involves improving characters such as yield performance and stability, resistance to pests and pathogens, grain and stem qualities and others.

Breeders have tapped genes for insect and disease resistance (Gowda *et al*. 1995), drought tolerance (Tsago *et al*. 2013), photosensitivity adaptation to climatic conditions (Obilana 1985), duration of growth period, response to low nitrogen level (Miri and Rana 2012), sugar accumulation in the stem for syrup and ethanol (Zheng 2011), high grain yield for food (Qazi *et al*. 2012) and high biomass yields for use as feedstock for animal or second generation biofuels (Srinivasa Rao *et al*. 2012).

Figure 6: Breeding fields of sorghum in South Africa (© Rutz)

In order to produce biomass of better quality, another important trait was tapped, which is the availability of brown midrib (bmr) mutations that is correlated to reduced lignin content and increased forage digestibility in animals (Srinivasa Rao *et al*. 2010), and favors a more efficient degradation of biomass for second generation biofuel (Dien *et al*. 2009).

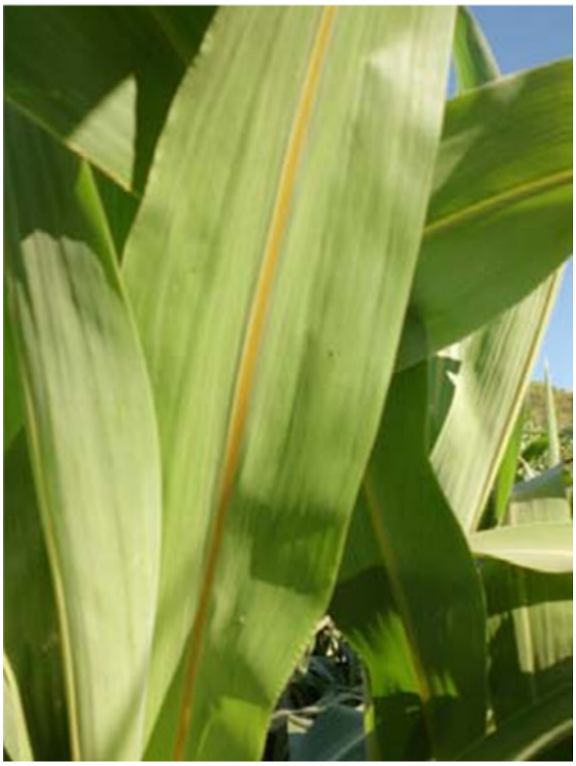


Figure 7: Brown midrib in sorghum leaves (© Braconnier)

Brown midrib (bmr) mutations in sorghum are phenotypically characterised by the presence of brown vascular tissues in the leaf blade and sheath (Figure 7) as well as in the stem. The value of a crop plant as forage is determined primarily by the degradability of the vegetative tissue and biomass production per time and unit area. Increased feedstock digestibility and degradation is negatively correlated with lignin (Blümmel and Rao 2006). Therefore, lignin is considered to be a rate limiting step in this process.

The SWEETFUEL project aimed at breeding improved cultivars and hybrids of sorghum. Thereby, the target ideotypes depended on the target environment and on the biofuel conversion process (Janssen *et al*. 2010). The following objectives were considered:

- In the temperate environments (e.g. Europe), the general objective is to develop sorghum hybrids with target ideotypes for high biomass, good adaptation to low temperature and good digestibility (low lignin content, bmr trait), suitable for 2nd generation bioethanol or biogas production. This is important in order to satisfy the biofuel policy of Europe in benefit of its farmers and agro-industrials and in respect of environmental concerns.

- In the tropical semi-arid environments (e.g. India), the general objective is to develop new lines or hybrids with target ideotypes for double purpose sorghum (grain + sugars) with good production of grain suitable for human or animal alimentation, high biomass production with juicy stems and high sugar content and good digestibility suitable for 1st generation ethanol production and cattle alimentation when bagasse is used as fodder. In addition, this new material should be better drought tolerant and adapted to rainy and/or post rainy season in India.

- In tropical savannahs (e.g. Brazil) with acid or low fertility, the general objective is to develop new lines or hybrids of sweet sorghum with target ideotypes for sorghum with juicy stems having high total sugar content, suitable for 1st generation bioethanol, and a good adaptation to marginal soils (acidity, high Al, low P).

2.5.2. Broad agro-ecological adaptation

Sorghum has a broad agro-ecological adaptation. It can be grown between 45°N and 45°S latitude on either side of the equator at elevations between mean sea level and 1,500 m. In most east African countries, it is grown between the altitudes of 900-1,500 m and cold-tolerant varieties are grown between 1,600 and 2,500m in Mexico. Sorghum can tolerate a temperature range of 12-37°C with an optimum temperature for growth and photosynthesis of 32-34°C and a day length of 10-14 h. Its optimum rainfall ranges from 550 to 800 mm with a relative humidity ranging from 15 to 50% (Srinivasa Rao and Kumar 2013).

Sorghum can adapt to a broad range of soil types and conditions. It can be grown in alfisols (red) or vertisols (black clay loamy) and tolerate a wide pH range from 5.5 to 8.5 (Du Plessis 2008). This broad spectrum makes sorghum a good candidate to be planted in acidic soils usually associated with phosphorus (P) deficiency and aluminium (Al) toxicity.

Sorghum is susceptible to sustained flooding, but will survive temporary waterlogging much better than corn. If the plant of sorghum has been immersed in flood for a week, it can re-grow quickly after the flood retreats.

2.5.3. Drought tolerance

Sorghum, called Camel among crops, will survive with a water supply of less than 300 mm over the season of 100 days, while it responds favourably with additional rainfall or irrigation water. Typically, sorghum needs between 550 to 800 mm of water (rain and/or irrigation) to achieve good yields, i.e. 50-100 t/ha total above ground biomass (fresh weight). Although sorghum is a dry land crop, sufficient moisture availability for plant growth is critically important for high yields. The major advantage of sorghum is that it can become dormant especially in vegetative phase under adverse conditions and can resume growth after relatively severe drought. Early drought stops growth before panicle initiation and the plant remains vegetative. It will resume leaf production and flower when conditions become again favourable for growth. Mid-season drought stops leaf development. During drought conditions the soluble sugars maintain the reasonable turgor level. In different sorghum genotypes the reducing sugars and the proteins are the indicators of drought tolerance (Erdei *et al*. 2009).

2.5.4. High water and radiation use efficiency

Water use efficiency (WUE) is defined as mm of water evapotranspired by the crop per kg of above-ground dry biomass or the biomass produced per unit of water consumed (Dercas and Liakatas 2007). Radiation use efficiency (RUE) is the conversion efficiency of intercepted radiation to dry matter expressed in g/MJ (Monteith 1993).

Sorghum efficiently (more than corn and other C4 crops) transforms the intercepted radiation (RUE = 3.7 g/m^2 of dry matter per MJ/m^2 of absorbed photosynthetically active radiation) and the used water into dry matter (WUE = 193 mm of water/kg of dry matter produced or 5.2 g of dry matter/kg of water consumed) (Gosse 1996).

It was found that aboveground dry biomass production from non-water-stressed sorghum plants suggests a high productivity potential among C4 crops (Curt *et al*. 1998). Under water shortage, radiation use efficiency may be significantly lower. Radiation use efficiency seems to be linearly related to water consumption. Stressed plants (probably except severely stressed) seem to use available water more efficiently than unstressed plants. The slope of the line relating dry matter produced and water evapo-transpired increases the sooner the stress is sensed (Dercas and Liakatas 2007).

2.5.5. High nitrogen use efficiency

High nitrogen use efficiency (NUE) is a desirable characteristic of plants for sustainable agriculture. NUE can be defined in many ways, but in a simple way, it is the nitrogen exported from the field in crop products over the nitrogen applied. Ra *et al*. (2012) calculated the nitrogen use efficiency (NUE) of various energy crops including sorghum, sugarcane and corn grown with a basal application of 72 kg/ha of N. The results showed that under conventional density plantation, sorghum had the highest NUE value of 120.8 kg/kg compared to corn and sugarcane which had a NUE value of 88.1 and 112 kg/kg respectively.

2.5.6. Salinity and alkalinity tolerance

Sorghum provides sufficient yields even when grown under stresses of soil salinity and reduced irrigation. Sorghum plants produce sufficient juice, total sugar and ethanol yields in fields with soil salinity up to 3.2 dS/m even though the plants receive 50-75% of the water regimes typically applied to sorghum. Therefore, sorghum may be viable as an alternative crop system under increased salinity and reduced irrigation conditions, especially in semi-saline and semi-arid fields where the irrigation water is limited during crop development (Vasilakoglou *et al*. 2011). In saline-alkaline soils, Xie *et al*. (2012) found that high sugar content and ethanol yield of sorghum can be acquired. Therefore, considering the competition between food crop and energy crop, it is advantageous to cultivate sorghum in saline-alkaline soils where very few other crops can grow.

2.5.7. Photoperiod sensitivity

Sorghum is a short-day plant, which means that the plant requires short days (long nights) before proceeding to the reproductive stage. Sorghum plants are most sensitive to photoperiod during flower initiation. The optimum photoperiod, which will induce flower formation, is between 10 and 11 hours. The tropical varieties are usually more sensitive to photoperiod than the quick, short-season varieties (Du Plessis 2008).

Most hybrids of sorghum are relatively less photoperiod-sensitive. Traditional farmers, particularly in West Africa, use photoperiod sensitive varieties. With photoperiod-sensitive types, flowering and grain maturity occur almost during the same calendar days regardless of planting date, so that even with delayed sowing, plants mature before soil moisture is depleted at the end of the season (Vaksmann *et al.* 1996).

2.5.8. Advantages in comparison with sugarcane

Table 1 shows a comparison between the two sugar producing crops sugarcane and sweet sorghum in regards to cultivation and ethanol production characteristics. This table reflects that sweet sorghum is more advantageous to be used as a bioenergy crop due to fewer requirements. Furthermore, ethanol production process from sweet sorghum is eco-friendly compared to that from molasses and the ethanol burning quality is superior - less sulphur than from sugarcane and high octane rating.

Table 1: Comparison among sugarcane and sweet sorghum (Almodares and Hatamipour 2011)

	Sugar cane	Sweet sorghum
Crop duration	About 7 months	About 4 months
Growing season	Only one season	One season in temperate and 2 or 3 seasons in tropical areas
Soil requirement	Grows well in drained soil	All types of drained soil except very sandy soils
Water management	36,000 m^3/ha	12,000 m^3/ha
Crop management	Requires good management	Little fertiliser required; less pest disease complex; easy management
Yield per ha	70-80 tons	54-69 tons
Sugar content on weight basis	10-12%	7-12%
Sugar yield	7-8 tons/ha	6-8 tons/ha
Ethanol production directly from juice	3,000-5,000 L/ha	3,000 L/ha
Harvesting	Mechanical harvest	Very simple; both manual and mechanical

3. Cultivation

3.1. Soil preparation

Sorghum seeds need a relatively warm, moist soil well supplied with air and fine enough to provide good seed-soil contact for optimal and rapid germination. A number of different tillage and planting systems can be used to get these conditions. These systems may involve primary or secondary tillage or no tillage operations prior to planting. An ideal seedbed should accomplish these goals:

- control weeds,
- conserve moisture,
- preserve or improve tilth,
- control wind and water erosion, and
- be suitable for planting and cultivating with available equipment.

One goal of seedbed preparation is to provide means of profitable crop production while minimising soil erosion due to wind and water. Tillage and planting systems accomplishing this goal are often referred to as conservation tillage systems (Vanderlip 1998).

3.2. Sowing

Density of plantation depends on variety, earliness, plant size, environmental conditions, etc and varies between 110,000 to more than 400,000 plants per ha. Figures will be less under tropical conditions. Planting in wider rows are recommended for the low rainfall areas and on soils with a poor water-holding capacity. Planting depth is also determined by soil type. On heavy soils, the planting depth should not be more than 25 mm, while on light soils the depth can be up to 50 mm. It is important that the soil surrounding the seed is firm to ensure rapid absorption of water and, eventually, germination (Sweethanol 2011b).

Taking into account the cycle length and the fact that the stage of sugar accumulation is affected by low temperatures, in the Mediterranean climates sowing should be performed at the beginning of May so that sorghum can be able to complete its cycle.

In Brazil, sweet sorghum is being proposed to be planted at the beginning of the rainy season in areas of sugarcane renovation to increase the period of operation of large distilleries by up to 100 days. Sowing therefore takes place between November and December and harvesting between March and April. The density of planting is between 120,000 to 130,000 plants per ha (Mantovani *et al*. 2012) (Figure 8).

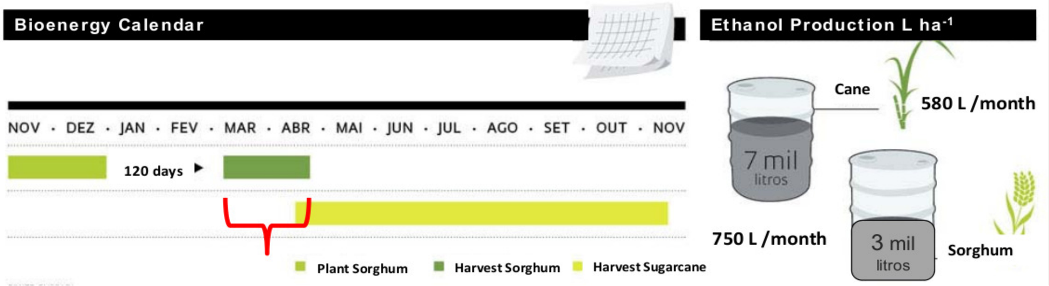


Figure 8: Bioethanol production calendar in Brazil (© EMBRAPA)

In India, sweet sorghum can be grown during the rainy season, post rainy season and summer season depending on the availability of irrigation sources and with suitable temperature regimes (Reddy 2013). The seeding density also differs according to the season. For the summer crop, it is between 80,000 and 160,000 plants per ha and it is less dense in the rainy and post rainy season.

- Rainy season (June-October): Sowing should be taken immediately after the onset of monsoon, preferably from the first week of June to the first week of July (depending on the onset of monsoon).
- Post rainy season (October-February): Planting should be done from the last week of September to the end of October. The night temperature should be above 15℃ at the time of sowing. The crop should be irrigated if there is no rainfall at the time of sowing to ensure uniform germination and establishment. Ridges and furrow method of planting should be followed to conserve irrigation water similar to the rainy season crop.
- Summer crop: Planting is done from the middle of January to the end of February under supplemental irrigated conditions. The night temperatures should be above 15℃ at the time of sowing. Summer planting on ridges and furrow will enable to realise excellent cane yield provided irrigation water is available.

In central Europe, it is advised not to sow when the temperatures are below 12℃ and that is usually before the middle of May. The seeding density varies depending on the variety and ranges from 240,000 (*Sorghum bicolor*) to 350,000 (*Sorghum bicolor* x *Sorghum sudanese*) plants per ha.

3.3. Fertilisation

Sorghum is considered very efficient in utilising nutrients from the soil because of a large fibrous root system.However, like other crops, sorghum needs adequate nutrients to produce good yields. Profitable responses to fertilisation can be expected on many soils. To assess the correct quantity of fertiliser to be applied for optimal yield, soil samples should be taken according to the recommendations of an accredited soil laboratory. Fertiliser recommendations made according to the soil analysis should be applied accordingly (Du Plessis 2008). In places where soil fertility ranges from low to moderate, the fertilisation needs are about: 100-150 kg N, 60-100 kg P_2O_5 and 60-100 kg K_2O per hectare. Nitrogen application is recommended to be done in two times: before sowing and 20-30 days after the emergence (Sweethanol 2011b).

3.4. Plant pests and control

Diseases of sorghum, like those of other crops, vary in severity from year to year and from one locality or field to another, depending on the environment, causal organisms, and the host plant's resistance. The total eradication of disease in sorghum is not economically feasible, so growers must try to minimise their damage through an integrated pest management system. Planting resistant hybrids, providing optimum growing conditions, rotating with other crops, removing infested debris, planting disease-free seed, proper seedbed preparation and accurate application of herbicides, insecticides, and fungicides are all methods that can be used to minimise losses from pests. Pests of sorghum are similar to corn and sugarcane in those areas where both are extensively cultivated.

3.4.1. Weeds

Since the first stages of the crop, namely from sowing to canopy closure, sorghum is very sensitive to weed competition. Many weeds can infest sorghum. One which can cause an important damage in some regions in the world is the root parasite *Striga spp.* or witch weed, which mainly occurs under low input farming conditions. Most of the damage is done before the parasite emerges from the soil. The symptoms include leaf wilting, leaf rolling, and leaf scorching even though the soil may have sufficient water. The tiny seeds are disseminated by wind, water and animals, and remain viable in the soil for 15 to 20 years. Weed control during the first 6 to 8 weeks after planting is crucial, as weeds compete vigorously with the crop for nutrients and water during this period. Rotation with cotton, groundnut, cowpea and pigeonpea will reduce the incidence of *Striga*. Hand pulling the plants before flowering may be useful.

For other weed species, the control include a mechanical removal by hand or with implements or by ploughing during winter or early spring or by applying chemicals in liquid, granule or gaseous form in order to kill germinating or growing weeds or seeds. Fields heavily infested with Johnson grass and Bermuda grass should not be planted with sorghum (Du Plessis 2008).

3.4.2. Bacterial and fungal Diseases

Four general types of diseases attack sorghum: those that rot the seed or kill the seedlings, those that attack the leaves and lower the value of the plants for forage, those that attack only the heads and so prevent the normal formation of grain, and those that cause root or stalk rots and prevent the normal development of the plant.

The most common disease known to attack sorghum and cause economic losses is the antrachnose. Caused by the fungus *Colletotrichum graminicola*, anthracnose is among the most important sorghum diseases in the world (Cardwell 1989). It infects all aboveground portions of the host (stalk, leaf, peduncle, panicle and grain) and develops in both living and dead tissue. Disease symptoms include a foliar phase, stalk rot, and panicle and grain anthracnose. Symptoms can vary due to differences in pathogen virulence or host resistance, or changes in physiological status of the host following infection. The most common and severe form of the disease is foliar anthracnose (Figure 9). Infection first appears on the leaves as small, circular or elliptical spots, which later enlarge and may unite to involve large areas of the leaf. The leaf midrib, which is commonly infected along with the leaf blade, is often strikingly discolored. Later the centers of the leaf spots fade to a grayish-tan color. Examination with a hand lens reveals the presence of numerous pin-point black specks with short, stiff hairs. Those are the fruiting bodies of the fungus, which, under moist conditions, produce pinkish spore masses. The spores are spread by rain and wind to other leaves, where they start new areas of infection (Smith and Frederiksen 2000).

Anthracnose can reduce the grain and fodder yield of susceptible cultivars by 50% and more (Harris *et al*. 1964; Harris and Sowell 1970). Anthracnose infection causes significant reduction in grain yield through reduced kernel weight and grain abortion (Thomas *et al.* 1996). Defoliation due to anthracnose reduces the value of the plants for forage and may reduce the sugar content of the stalks in very susceptible varieties. It also may lower the ratio of sucrose to invert sugars.

Figure 9: Symptoms of leaf anthracnose (© Viana Cota)

Clean culture and rotation to avoid planting sorghum in fields cropped the previous year with Sudan grass, sorghum, or Johnson grass should reduce the losses caused by anthracnose. Host plant resistance is the most economical approach for successful management of the disease. Availability of resistance sources is a prerequisite for breeding adapted, resistant and productive sorghum cultivars. Table 2 lists the other diseases that may attack sorghum.

Table 2: Pathogenic diseases that may attack energy sorghum

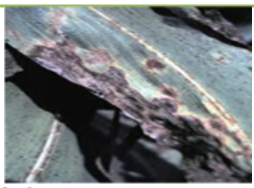
1. Pathogens that may attack the seed and seedling

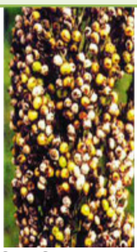
Disease & Pathogen	Symptoms	Control
Seed rot: species of *Fusarium, Aspergillus, Rhizopus, Rhizoctonia, Penicillium*, and *Helminthosporium*	They invade and destroy the endosperm, the starchy tissue of the seed, thus robbing it of the food necessary to produce a strong seedling.	A careful selection and treatment of seed and proper cultural practices should be done. Seeds should be well matured and properly dried. The seed coat should be as free as possible from cracks and nicks. Before being planted, the seeds should be treated with a good disinfectant that will protect them from seed-born fungi and, to a great extent, from the harmful fungi in the soil.
Pythium	It attacks the young sprout in its early stage and prevents its emergence.	

2. Bacterial pathogens that may attack the leaves

	Disease & Pathogen	Symptoms	Control
 © Cunfer	Bacterial stripe: *Xanthomonas campestris* pv. *Holcicola*	Lesions are narrow and elongated between the leaf veins. Lesions begin as a thin red band along the vein, and then expand to produce a dark red to black border and a grey centre of dead tissue. Masses of bacterial cells in the lesions exude to the surface when leaves are wet.	Control of these bacteria includes crop rotation, planting resistant cultivars, sanitation, seed treatment and disposing of old infected plant litter and infected plants that overwinter.
 © Wrather	Bacterial streak: *Pseudomonas andropogonis*	The bacteria cause narrow, yellow stripes. Eventually, red-brown blotches appear in the streaks, which may broaden into oval spots with tan centres and narrow, red margins.	
 © Howard	Bacterial spot: *Pseudomonas syringae* pv. *syringae*	Bacterial spot, caused by Pseudomonas syringae, is characterised by small, irregular shaped, tan lesions with dark margin.	

3. Fungal pathogens that may attack the leaves

	Disease & Pathogen	Symptoms	Control
 © Luciana Viana Cota	Leaf Blight: *Exserohilum turcicum*	Small reddish or tan spots that can enlarge to long elliptical reddish purple or tan lesions appear. Sporulation on lesions often gives them a dark grey or olive appearance on the surface.	Resistant cultivars and rotation are recommended. High yielding and resistant cultivars and hybrids have been identified and are available to growers.
 © Luciana Viana Cota	Cercospora leaf spot: *Cercospora fusimaculans*	Small circular to elliptical dark purple or red spots appear. Later, the centre becomes tan or brown and spots elongate with grey spore masses covering the spots.	Use of resistant cultivars is recommended. Most varieties have adequate tolerance to this disease. Rotation and avoiding working when plants are wet are also recommended.
 © Wrather	Zonate leaf spot: *Gloeocercospora sorghi*	It is of little or moderate importance. Very large circular lesions that have alternating straw coloured and purple rings appear.	Crop rotation and cultivation to control susceptible weed hosts are recommended. Cultivars and hybrids that are somewhat resistant are available to growers.
 © Cunfer	Rough spot: *Ascochyta sorghina*	Light-coloured spots appear in the beginning and turn to rough black specks caused by the raised black fruiting bodies (pycnidia).	Sorghum should not be grown on land where rough spot occurred the preceding season. Seed treatment and the use of available resistant varieties are advisable.
 © Luciana Viana Cota	Sooty stripe: *Ramulispora sorghi*	Lesions are elliptical in shape. They have a cream to tan coloured centre with a reddish purple or tan margin. A very broad, yellow halo characteristically surrounds the lesion. Mature lesions become black or sooty.	Cultivating resistant varieties and removal of harvesting residues as well as secondary hosts are recommended.
 © Luciano Viana Cota	Rust: *Puccinia purpurea*	Nearly all sorghum hybrids will sustain some foliar damage from sooty stripe. The best method of reducing sooty stripe is rotation.	Small raised pustules or blisters that rupture and release many reddish-brown spores appear. These pustules occur on both the upper and lower leaf surfaces.
 © ICRISAT	Downey mildew: *Peronosclerospora sorghi*	The symptoms include chlorotic foliage and stunted plants resulting in death of seedlings. The first infected leaf shows chlorosis on the lower part of the lamina. Under cool and humid conditions, the below surface of chlorotic leaves produce abundant white spores. As the plant grows, new emerging leaves exhibit parallel stripes of green and white tissue.	The control measures to be taken are to plant resistant varieties, to rotate with cotton, wheat, soybeans or a forage crop and to remove and eradicate the diseased seedlings to prevent the spread of the disease.

4. Fungal pathogens that may attack the head or panicle			
	Disease & Pathogen	**Symptoms**	**Control**
 © ICRISAT	Head or grain mold : *Fusarium moniliforme, and other spp.Curvularia lunata, Phoma sorghina, Helminthosporium spp. and Alternaria spp.*	On heads infected by *Fusarium*, seeds are pink, orange or white and by those infected by *Curvularia, Alternaria* or *Helminthosporium* the seeds are black.	Grain mold can be avoided either by delaying sowing dates or by growing medium- to late-maturing cultivars in such a way that maturity stages occur after end of the rains. Host plant resistance is the most preferred method of control.
 © ICRISAT	Ergot: *Claviceps Africana Ergot*	The fungus usually only infects unfertilized flowers and infection results in the production of a sugary exudate on the infected flowers (honeydew). After maturity, the infected seed produces an elongated black horn. It can reduce crop yield and cause toxicity problems in livestock feeding on heavily contaminated grain.	The disease can be controlled by rotation and by planting cultivars and hybrids that are resistant to infection.
 © ICRISAT	covered kernel smut: *Sporisorium sorghi*	In smutted heads, enlarged cylindrical or cone-shaped smut galls are formed instead of the kernels. At first the smut galls are covered with a light grey or brown membrane that later may break and release the dark-brown spores. Affected plants appear normal except for the smutted heads.	Seed treatment and the use of smut-free seeds and resistant varieties are the most efficient control measures for all smut diseases.
 © ICRISAT	loose kernel smut: *Sporisorium cruenta*	The galls formed by loose kernel smut are long and pointed. The thin membrane over them usually breaks soon after the galls reach full size. Most of the dark-brown spores are soon blown away, leaving a long, dark, pointed, curved structure, called a columella, in the central part of what was the gall.	
 © ICRISAT	head smut: *Sporisorium reiliana*	It is distinguishable from the kernel smuts because it destroys the entire head, transforming it into a large mass of dark-brown, powdery chlamydospores. This smut fungus is carried in the soil. Sorghum grown from clean seed planted on infested soil may be attacked.	
 © ICRISAT	Long smut: *Sporisorium ehrenbergii*	Long smuts appears as elongated, cylindrical, slightly curved sori which have a whitish thin membrane that ruptures to release a black powdery mass of spore balls that can be easily blown by the wind. The sori are unevenly distributed on the panicle, unlike the covered smut sori.	

5. Pathogens that may attack the root and stalk			
	Disease & Pathogen	**Symptoms**	**Control**
 © ICRISAT	Charcoal rot *Macrophomina phaseolina* or (*Sclerotium bataticola*)	It is the most destructive of the stalk rots. It is unpredictable and more or less sporadic in its appearance. One symptom of the disease is lodging; however, diagnosis of infection by this disease is best characterised by a dried, stringy appearance of the stem near the soil line and the presence of black sclerotia in the affected areas.	Incidence of charcoal rot can be minimized by maintaining soil moisture during the post-flowering stages. High levels of nitrogen and low levels of potassium are conditions that should be avoided. Sterile plants are essentially immune.
 © Wrather	Fusarium stalk rot *Fusarium thapsinum*	Fusarium stalk rot causes the pith in the lower stalk to appear red while the outside of the stalk remains green. The pith tissue usually remains intact, unlike the shredding associated with charcoal rot. Plants may die prematurely or lodge.	It is recommended to plant in a fertile soil, to plant varieties with good stalk strength, to avoid high plant populations unless irrigating and to avoid drought stress conditions through reduced tillage or irrigation.

3.4.3. Viral diseases

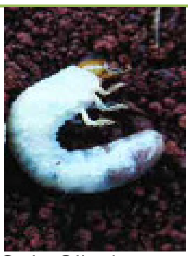
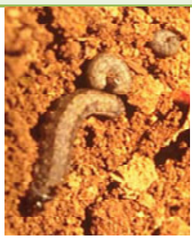
The virus that has been known to cause injury to sorghum is maize dwarf mosaic virus (MDMV), but only in fields where Johnson grass is present. The virus overwinters in the underground rhizomes of Johnson grass. Shoots produced from these rhizomes in spring will be infected, and the virus can be transmitted by aphids (corn leaf aphid and greenbugs) from those shoots to other susceptible plants like corn. MDMV-infected plants exhibit a distinctive mottling of leaves. When compared with healthy leaves, diseased leaves are yellow with light green islands. These symptoms are more evident on young than on old leaves. Symptoms generally are less visible on plants in the boot stage. Mottling is the most common leaf symptom, but other symptoms may occur. When temperatures fall below 13℃, infected leaves may turn red, and then elongated tan stripes with red margins develop on the leaves. Severely infected plants frequently die, while those that survive will be stunted and may fail to produce a normal head.

The control procedures are mainly planting tolerant varieties and eliminating rhizome Johnson grass in the field. Killing the aphids that spread the disease will not reduce MDMV infections. Thus, use of insecticides in the management of MDMV is not recommended.

3.4.4. Insect pests

A wide variety of insect pests can affect sorghum throughout its life cycle. Insect pressure depends on location, weather and growth stage of the crop. The most common insects that may attack sorghum can be grouped into four categories: insects attacking seeds and roots, insects and mites attacking leaves and leaf whorls, stalk borers and insects attacking panicles (Table 3).

Table 3: Sorghum insect pests

1. Insects attacking seeds and roots			
	Name	**Symptoms**	**Control**
 © Viana	Wireworms: *Aeolus, Eleodes, Conoderus spp*	They feed on and damage planted sorghum seeds. Wireworms feed less on seedling roots. Seeds hollowed out by larvae do not germinate, thus reducing plant stand. Evidence of wireworm damage to sorghum is a non-uniform plant stand with stunted, weak seedlings.	It is recommended to plant sorghum in a field where a non-grass crop was grown the previous year, to apply insecticide to seeds and to purchase seeds already treated with a systemic insecticide. When wireworms are abundant, an insecticide should be additionally applied to soil at planting.
 © Wild	Red Imported Fire Ant: *Solenopsis invicta*	They feed on planted sorghum seeds. They occasionally damage roots and leaflets of germinating seeds. Worker ants chew through the thin seed coat and remove the embryo (germ). This damage results in loss of seed germination, causing reduced sorghum plant stands.	It is recommended to plant sorghum in a field where a non-grass crop was grown the previous year, to ensure a rapid seed germination, to implement extensive tillage on fields and to use seeds treated with insecticide.
 © de Oliveira	White Grub: *Phyllophaga crinite*	Damage results from larvae feeding on roots. After germination, damage to roots causes seedlings less than 15 cm tall to die. Stand loss can occur within 7 to 10 days after plants emerge. Infested plants not killed as seedlings are severely stunted and may never produce grain. Root pruning may also occur.	It is recommended to plant sorghum in a field where a non-grass crop was grown the previous year and to use insecticide at planting. Preplant application of insecticides is effective but expensive because the insecticide must be broadcast and then incorporated into the soil.
2. Insects attacking seedlings			
	Name	**Symptoms**	**Control**
 © Texas A&M AgriLife Extension	Cutworms: many spp, Family *Noctuidae*	Some cut off sorghum plants at or slightly below the surface of the soil (surface-feeding cutworms). Some feed on above-ground plant parts (climbing or army cutworms) and others feed on underground plant parts including roots of seedlings (subterranean cutworms). Plants with severed stems die. Leaf feeding by cutworms causes ragged leaves, while root-feeding cutworms kill small plants or stunt larger plants.	It is recommended to perform tillage to destroy vegetation in late summer or early fall. Herbicides may be used to kill winter weeds. Insecticide can be used, but effectiveness of control can vary greatly. Subterranean cutworms can be suppressed with insecticide applied to soil at planting.
 © Bradshaw	Southern Corn Rootworm: *Diabrotica undecimpunctata howardi*	It feeds on and bores into roots of sorghum or enters the stalk just above the roots. It destroys the apical meristem and prevent growth of the main stem. Symptoms of damage are stunting and "deadhearts." Delayed and non-uniform maturity may result from production of tillers. Plant lodging may occur later in the season.	Control can be done by keeping fields free of grassy weeds, ploughing and disking thirty days before planting, rotating with a non-grass crop, planting early, and at a slightly higher than normal seeding rate. At planting application of granular or liquid insecticide also is effective.
 © Nuessly	Yellow Sugarcane Aphid: *Sipha flava*	They feed on the underside of lower sorghum leaves and inject toxin. Aphids cause purple-coloured leaves on seedlings. Plants not killed are severely stunted, and maturity is delayed. By the time discoloration symptoms are visible, plants have been injured significantly. Damage often causes plant lodging that may be enhanced by associated stalk rots.	Many predators feed on the yellow sugarcane aphid, but the aphid rarely is parasitized. Rapid seedling growth is important. Several foliar insecticides effectively control them. Some systemic insecticides applied to seed or in-furrow at planting also control them.

2. Insects attacking seedlings

	Name	Symptoms	Control
 © ICRISAT	Sugarcane aphid: *Melanaphis sacchari*	These aphids prefer to feed on the under surface of older leaves. The damage proceeds from the lower to the upper leaves. The adults and nymphs are yellow. They suck the sap from the lower surface of leaves resulting in yellowing and stunted plant growth. The damage is more severe in crops under drought stress, resulting in drying of leaves and plant mortality. Sooty mold can grow on the secreted honeydew.	Destruction of the overwintering host plant is considered very important to reduce the aphid population in sorghum fields. it is suggested to plant early with high plant density and cut forage sorghum before the first week of aphid appearance.
 © K-State University	Chinch Bug: *Blissus leucopterus*	Chinch bug adults and nymphs damage plants by withdrawing large amounts of juices from stems or underground plant parts. Young plants are highly susceptible to damage. Older plants withstand more than smaller plants, but they, too, become reddened, weakened, and stunted, and frequently lodge. Chinch bug outbreaks are favoured by dry weather.	Systemic insecticide applied for soil insect pests to seed or at planting for soil insect pests control chinch bugs. Insecticide applied by aircraft seldom is effective or recommended.

3. Insects and mites attacking leaves and leaf whorls

	Name	Symptoms	Control
 © Mendes	Corn Leaf Aphid: *Rhopalosiphum maidis*	It is most frequently found deep in the whorl of the middle leaf of preboot sorghum, but also on the underside of leaves, on stems, or in panicles. Adults and nymphs feed on plant juices but do not inject toxin. The most apparent symptom is a yellow mottling of leaves. Sometimes molds grow on the honeydew produced. Honeydew on the panicle can hinder harvest. The aphid also transmits MDMV.	Yield losses occur only where corn leaf aphids cause stand loss of seedling plants. Occasionally, corn leaf aphids become so abundant on a few plants in a field that panicle exertion and development are hindered. Although this aphid does not need to be controlled, it can be controlled with insecticides, especially systemic ones
 © Araújo	Greenbug: *Schizaphis graminum*	It is considered a key insect pest of sorghum. The aphids suck juices from plants and injects toxin into them. They feed on the underside of leaves and produce much honeydew. They often do not reach damaging numbers until the sorghum panicle develops. Infestations may be detected by the appearance on leaves of reddish spots caused by the toxin injected. Damaged leaves begin to die, turning yellow and then brown from the outer edges. They also transmit MDMV and may predispose sorghum to charcoal rot.	Rainfall and predators suppress increase in greenbug abundance early in the season. The parasite, *Lysiphlebus testaceipes*, usually is responsible for rapid decline in aphid abundance late in the season. Sorghum hybrids resistant to greenbug should be used. Greenbugs can be controlled by some insecticides but is resistant to several.
 © ICRISAT	Banks Grass Mite: *Oligonychus pratensis*	Spider mites suck juices from the underside of sorghum leaves. Infested areas of leaves are pale yellow on the top surface and later become reddish. Leaves may die. However, yield loss may occur after the hard-dough stage if spider mites are abundant enough to cause lodging and related harvest losses.	It is advised not to plant sorghum next to wheat. The application of insecticide is justified when one-third of the leaves of most sorghum plants in a field are infested with mites. Thorough coverage with the spray mixture is required. Insecticides may not provide effective control because spider mites often are resistant.

4. Stalk borers

	Name	Symptoms	Control
 © Mendes	-Sugarcane Borer: *Diatraea saccharalis* -Neotropical Borer: *D. lineolata* -Southwestern Corn Borer: *D. grandiosella*	Young larvae feed for a few days on leaves or the leaf axis. Older larvae tunnel into and bore up and down the pith of the stalk. Infested stalks are smaller in diameter, and may lodge. Boring by larvae often causes the peduncle to break and panicle to fall. Injury by borers makes the plant more susceptible to stalk rot pathogens.	It is recommended to plant sorghum early and to plough in order to break stubble and bury crop residues soon after harvest destroys overwintering larvae by exposing them to cold temperatures. Chemical control rarely is justified.
 © Ward	Sugarcane Rootstock Weevil: *Anacentrinus deplanatus*	Adult weevils feed on young sorghum plants and rootstocks. This damage is noticeable but not as serious as that caused by larvae. Larvae tunnel into the sorghum stalk below or just above the surface of the soil. Their feeding often is responsible for the drought-stressed appearance and lodging of sorghum plants. Exit holes and feeding tunnels allow pathogens such as charcoal rot to enter the plant.	Sugarcane rootstock weevil sporadically infests sorghum, especially during dry years. Good cultural practices that promote early and vigorous plant development are beneficial against this insect. Effective insecticides and application techniques are not available.

5. Insects attacking panicles

	Name	Symptoms	Control
 © ICRISAT	Sorghum Midge: *Stenodiplosis sorghicola*	Sorghum midge larvae feed on the newly-fertilized ovary, preventing kernel development and causing direct grain loss. Glumes of a sorghum midge-infested spikelet fit tightly together because no kernel develops. Typically, a sorghum panicle infested by sorghum midge will have, depending on the degree of damage, various proportions of normal kernels scattered among non-kernel-bearing spikelets.	Planting hybrids with uniform maturity and early is the most effective cultural management method. It prevents late flowering and avoids damaging infestations. Deep ploughing sorghum residues kills some overwintering larvae. Multiple insecticide applications prevent damage when sorghum is planted too late to escape damaging infestations.
Corn earworm: *Helicoverpa armigera*  © ICRISAT	Earhead caterpillar: *Eublemma silicula*  © ICRISAT	The corn earworm and the earhead caterpillar feed on the developing grain. They destroy the grains mostly from the inside of the panicle. Some species produce webs of silken threads inside the panicle or make small holes in the grain. In cultivars with compact panicles, the inside of the panicle may be completely damaged while the panicle may look healthy from the outside. Feeding on the developing grain causes maximum loss in grain yield. These caterpillars cause heavy damage under humid conditions.	They can be controlled by using traps with the pest's synthetic sexual pheromones, destroying left over material from crops, releasing natural enemies like the *Trichogramma pretiosum* fungus, using selective pesticides and using microbial agents like baculovirus and *Bacillus thuringiensis*.
 © Mendes	Fall Armyworm: *Spodoptera frugiperda*	Fall armyworms infest both the whorl and panicle of sorghum. They feed on the whorls until the panicles start to emerge. Young, small larvae feed first on florets. As larvae grow, they feed on developing kernels. Most damage to kernels is caused by larger larvae and about 80% of damage is by the last two larval instars.	Several wasps and flies parasitize, several bugs and beetles prey, and pathogens, especially fungi, infect and kill fall armyworm larvae. Planting early is an important management tactic to escape infestation. Using sorghum hybrids with loose panicles is an effective management practice.

5. Insects attacking panicles			
	Name	**Symptoms**	**Control**
 © ICRISAT	**Panicle-Feeding Bugs** *Oebalus pugnax* *Nezara viridula* *Chlorochroa ligata* *Leptoglossus phyllopus* *Nysius raphanus* *Calocoris angustatus*	These bugs have similar natures and symptoms of damage. They suck juices from developing grain. They may cause economic damage, depending on the number of bugs per panicle, duration of the infestation, and stage of kernel development when infestation occurs. Kernels in the hard-dough stage usually are not damaged. Both nymphs and adults reduce kernel weight, size, and quality. Fungi often infect and cause damaged.	For most species, an infestation of sixteen or more bugs per panicle at the hard-dough stage of kernel development is required to justify insecticide.

3.4.5. Nematodes

Plant-parasitic nematodes have been shown to cause yield losses in sorghum (Claflin 1983). *Meloidogyne, Tylenchorhynchus, Belonolaimus, Pratylenchus, Xiphinema*, and *Trichodorus* are important genera in the evaluation of possible nematode damage in sorghum. Nematology research utilising sorghum as the host crop is very limited. The potential interrelationships of fungi, bacteria, and nematodes as they relate to the stalk rot complex in sorghum have not been researched in depth. Table 4 lists those nematode genera that are cosmopolitan and are most likely to be implicated in sorghum yield losses.

Table 4: Plant-parasitic nematode genera that are pathogenic on sorghum (Claflin 1983)

Nematode	Mode of parasitism	Characteristic symptoms	Hosts other than sorghum
Root-lesion (*Pratylenchus spp*)	Endoparasitic	Decline in plant vigour, necrotic root lesions, association with microorganisms in causing disease complexes, low kernel test weight	Grasses, cereals, cabbage beet, tomato, legumes, tobacco; over 400 hosts
Root-knot (*Meloidogyne spp*)	Endoparasitic	Decline in plant vigour, stunting, root galls, proliferation of branch roots, reduced stands, delay in flowering	Grasses, cereals, legumes, cotton, tobacco, tomato, potato
Stunt (*Tylenchorhynchus spp*)	Ectoparasitic	Stunting, lack of root development, decline of seedling vigour, root tips may be short and thickened	Grasses, cereals, legumes
Sting (*Belonolaimus spp*)	Ectoparasitic	Decline in plant vigour, stunting, root systems with very limited development, threshold level in corn is 1 sting nematode/100 cm^3 soil, generally only detected in sandy soils	Cotton, cereals, legumes, vegetables, tobacco
Dagger (*Xiphenema spp*)	Ectoparasitic	Decline in vigour, poor root development, extensive necrosis of root tissue	Citrus, fruit and shade trees, cereals, grasses, legumes, vegetables

4. Harvesting and logistics

Harvesting and logistics of energy sorghum differs according to the end product use. Three main harvesting methods are distinguished: If sorghum is planted only for first generation bioethanol production (e.g. Brazil), if it is planted for both first generation bioethanol and grain production (e.g. India) and if it is planted for second generation bioethanol or biogas production (e.g. Europe).

- **Harvest of stalks (1st generation bioethanol):**

The ideal time for harvesting and period of industrial utilisation are determined by the values of Brix, total and reducing sugars and percentage of both, the curve of maturation of each cultivar, time length from the tenth day after flowering until the maturity stage of the grain, and depending on varieties, 30 to 60 days after flowering. According to Schaffert *et al.* (1980), the process of accumulation of sugars in sweet sorghum increases after reaching the flowering stage and continues until the stage of physiological maturity of the grains.

In Brazil new hybrids have been developed, which can be harvested after 100 to 120 days. In order to determine the best time for harvesting, the amount of sugar in the juice should be measured with a Brix hydrometer or a sugar refractometer during the periods mentioned above. Harvesting should start when the total sugar content in the juice is 12.5% (Mantovani *et al.* 2012) or when an approximate reading of 15.5° to 16.5° Brix is reached (Bitzer and Fox 2000).

Currently, there are no harvesters especially made for sweet sorghum. For large scale plantations, harvesting of sweet sorghum is being done by using the same harvesters of other crops such as sugar cane (Figure 10). Some equipment are being designed, developed and tested in Brazil. A harvester equipped with a tool which permits the collection of the cut panicles instead of being left on the field would be ideal. The planting is carried out according to the necessary spacing for these machines and double spacing of 0.60 m / 0.90 m has been the most common. With the increased demand of the industrial sector to process the harvested material (stem cuts of 20 cm) for the production of alcohol, adjustments in cutting cylinders are being made and future cuts could be realised given the exigencies of the plants. The recommendation to cut the stems by the harvesting equipment is 20 cm, considering that the production fields are not located far from the mills (Mantovani *et al.* 2012).

Table 5: Effects of sweet sorghum sugar content by delay in crushing (Reddy *et al.* 2008)

Crushing (days after harvest)	Juice extraction (L x 103 / ha)	Brix reading	Sugar yield (Mg/ha)	Sugar reduction from harvest day (%)
0	42.4	18.5	2.62	-
1	40.6	19.2	2.47	5.7
2	35.0	20.9	2.18	16.8
3	37.6	21.4	2.20	16.0

Figure 10: Harvester adjusted for harvesting sweet sorghum (© EMBRAPA)

Sweet sorghum is similar to sugar cane in that the juice (sugar) in the stalk needs to be processed fairly rapidly, otherwise sugars in the stalk are lost and the quality of the juice is deteriorated. Given that the sugar in sweet sorghum, like in sugar cane, needs to be processed rapidly, technologies need to be developed to stabilise the juice and maintain the sugar for later processing so that the processing season for the sugar could be extended. In addition, if the stalks are not processed immediately, they will have to be unloaded, stored and uploaded again, which increases the costs.

- **Harvest of grains and stalks (food and 1 st generation bioethanol):**

Grain sorghum crop is usually harvested in a similar way as are other small grains, such as wheat. In modern agriculture, grain sorghums have been bred for uniform height so they may be efficiently harvested with a combine. Sweet sorghum varieties bred for both grain and stalk are much taller than the traditional grain sorghum varieties. Therefore, the conventional machines cannot be used for harvesting.

In India, currently harvesting is done manually. At a first stage the whole plant is cut and at a second stage the panicles are removed and collected (Figure 11). New harvesting methods suited to both grain and stem harvesting are being tested in Australia (Agrifuels 2009).

The time of harvesting is very important for the dual purpose sweet sorghum and varies according to the variety. Suitable date for harvesting should be determined according to fresh stem yield, juice rate, sugar degree and grain yield (FAO 1994).

Figure 11: Manual harvesting of the dual purpose sweet sorghum in India (© Braconnier)

- **Harvest of whole plant (2nd generation bioethanol or biogas):**

Tall sorghums are harvested with a forage harvester (Figure 12). High tonnages require large self-propelled harvesters, which have high capital costs. However, field and road conditions may not permit, either physically or economically, the use of large-scale harvest equipment and it may make sense to use a tractor-pulled forage harvester. Pari *et al* (2008) reported on European efforts to develop a sorghum harvester appropriately scaled to European conditions.

Harvest timing depends on when biomass is needed, variety type, season length, time of planting and desired moisture parameters. In temperate zones, harvesting usually occurs between September and October for biogas production.

Another option in temperate zones could be to plant sorghum after a winter crop. After harvesting the winter crop in June, sorghum can be sown. It will not have enough time to complete all the cycle, but it can be harvested by November giving a good biomass yield for 2nd generation bioethanol, and at a time which does not correspond to harvest of other biomass crops.

Figure 12: Energy sorghum harvested as a cellulosic bioenergy feedstock with a forage harvester (© Jordan)

The two most common methods for harvesting sorghums for biomass are swathing followed by baling or chopping of windrows, and direct forage chopping of the standing crop. A key consideration in choosing between the two methods is the optimum final moisture content of biomass for the desired end use, as well as what level of subsequent drying is needed to achieve it. Arguably, the most convenient method for harvesting biomass sorghum is to direct chop the standing material into a truck as it passes through the field. This method minimises dirt in the harvested material. However, it also requires rapid processing of the harvested biomass because the sugars present in the freshly chopped material will contribute to its degradation. Using a swather to cut and windrow for later pickup is another way to harvest and dry sorghum for biomass. This method allows the biomass to be field-dried before final pickup, when drier material is required or field storage is preferred (Blade Energy Crops 2010). For biogas production, the chopped material can be stored as silage and processed later. The degradation is therefore avoided.

5. Applications of energy sorghum

The sorghum crop can be separated into three main parts (panicle, leaves and stalk), each utilised for the production of a variety of products such as feed, food, sugar syrup, fibre, compost and biofuels. Energy sorghum can be converted into energy carriers through either one of two pathways: biochemical and thermo-chemical. Through biochemical processes the crop sugars can be converted to biofuels (first and second generation ethanol, biogas). Thermo-chemical processes such as combustion, pyrolysis and gasification can be used for the conversion of energy sorghum to heat and electricity. Figure 13 shows the different use options of energy sorghum parts and the undergone processes for the production of the previously mentioned products.

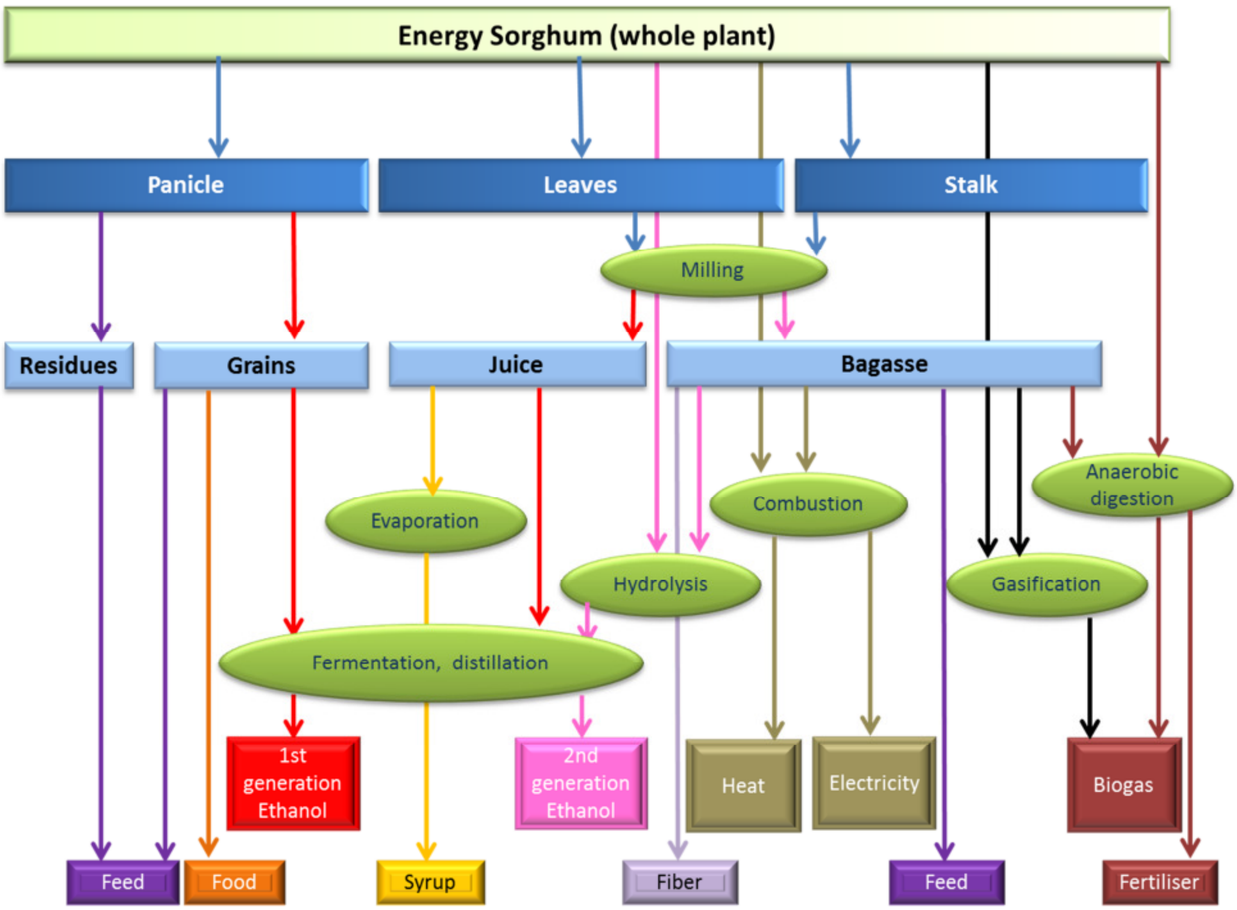


Figure 13: The different processes that energy sorghum can undergo and the resulting products

5.1. Syrup production

Sweet sorghum syrup production offers farmers an excellent opportunity to improve farm income and productivity. It is ideally suited for the small landowner with limited capital. Sweet sorghum syrup can be an attractive marketable product. Excellent syrup can be made when brix of raw juice is greater than 15%. In small-scale production units, usually no chemicals are added in making the syrup. This is in contrast to industrial sugarcane syrup/jaggery production where normally various chemicals are added mainly to improve the colour of the product.

The yield and quality of sweet sorghum syrup are influenced by the equipment and process used in manufacturing and by the syrup makers knowledge and skills. Some of the major reasons for poor quality syrup are presence of settled as well as floating mass in syrup or general cloudy appearance due to inadequate removal of scum, gelling of syrup due to high quantity of starch in juice, crystallisation due to high concentration of sucrose in juice and very low or high viscosity of syrup produced due to faulty recording of brix and/or temperature of syrup (Nimbkar *et al.* 2006).

In India in small-scale production after harvesting the stalks are stored in shade for one or two days before milling for juice extraction. This conditioning allows the inversion of sucrose to reducing sugars and thus improves the quality of juice. Conditioning of stalks before milling also removes excess moisture from the stalks and increases the brix of juice which ultimately helps to reduce the time and fuel required for syrup concentration. A crusher is then used to crush the millable stalk for extraction of the juice.

In places where harvesting is totally mechanised, the stalks are cut into pieces during harvesting. In this case the stem cuts are taken immediately for juice extraction since the quality of the juice will deteriorate if it is kept for a long time before processing.

Sweet sorghum juice has low purity. Apart from sugars, it contains soluble solids like anthocyanins and chlorophyll and insoluble solids such as starch granules. The extracted juice should be strained to remove big pieces of crushed material and then strained through a fine mesh screen to the settling tank in order to get clean juice. The strained juice should be kept undisturbed for 1-2 hours for settlement of starch granules.

The supernatant juice (keep at least 3-4 cm juice from the bottom of the tank undisturbed) is then pumped into a pan where the evaporation takes place. This is the most critical aspect of making high quality syrup. Good quality syrup can be made after carrying out evaporation with continuous skimming of coagulated materials, which have risen to the surface. Slow heating is required when frothing starts, as otherwise the syrup will get burned. When the temperature reaches 105-107°C with a brix of 74 to 76%, heating should be completely stopped. If quick cooling is not carried out, the product will have a burnt taste and the colour of the syrup will become dark brown. Therefore, the syrup should be cooled to 80°C within 10-15 minutes of preparation before filling it into sterilised bottles (Nimbkar *et al.* 2006).

5.2. First generation bioethanol production

Nowadays, 40% of the total energy consumption worldwide is in the form of liquid fuels such as petrol and diesel. In fact, the transport sector is almost fully dependent on this kind of fuel. Hence, special attention has been given to the potential use of biofuel in vehicles. Among biofuels, ethanol is one of the most environmentally appealing. It can be blended with petrol at a ratio of 10% ethanol (E10) to operate in normal vehicles or at a ratio of 85% ethanol (E85) to operate in flexible fuel vehicles (FFV) (Figure 14). Even a 100% ethanol fuel can be used in dedicated FFVs.

Figure 14: FFVs at a trade fair (© Rutz)

Bioethanol is derived from the alcoholic fermentation of simple sugars or starch (first generation bioethanol) or polysaccharides (second generation bioethanol) under anaerobic conditions. In the presence of water and yeasts (*Saccharomyces cerevisiae*), glucose is converted into ethanol, CO_2 as well as smaller quantities of minor end products such as glycerol, fusel oils, aldehydes and ketones.

Sweet sorghum stalks contain up to 75% juice, varying between 12 and 23% in sugar. Sorghum juice-derived ethanol is cheaper to produce than corn ethanol because it doesn't require the long fermentation and cooking that corn requires for conversion of starch to sugar to fuel grade alcohol (Dweikat 2012). The taller the plant and the thicker the stalk, the more juice the plant will produce. In addition, sweet sorghum has high amount of sucrose and invert sugar which are easily converted to ethanol. Furthermore, the cost to cultivate sweet sorghum can be three times lower than that of sugarcane (Reddy *et al*. 2005).

Extraction of juice for ethanol production is the same as for syrup production. Figure 15 shows the first mill in the process of juice extraction and Figure 16 shows the bagasse left after the juice was extracted.

For on-farm ethanol production from sweet sorghum, Bele (2007) cited a process involving harvesting and pressing the sweet sorghum stalks using a new mobile field harvester (patent pending) with a multi-roller press and juice collection unit mounted on the harvester. The harvester accomplishes both harvest and juice expression in a single pass through the field. The unit uses a standard forage chopper/header and feed rollers. After the stalks are pressed, they are expelled back onto the field. Juice is then pumped from the harvester directly into large storage bladders which are placed in the field, where fermentation takes place.

Figure 15: First mill in the process of sweet sorghum juice extraction (© Braconnier)

Figure 16: Bagasse left after juice extraction (© Braconnier)

The fermentation process can be operated either in a fed-batch (75% of the distilleries) fermentation system (Figure 17) or in a continuous system, both utilising yeast cell recycling. In the continuous process, the fermentation yield is higher than in the batch process and the total volume necessary is less than the other alternative, but the main problem with this system is the risk of contamination with bacteria (Sweethanol 2011a). In both processes, after the end of fermentation, yeast cells are collected by centrifugation and re-used in a next fermentation cycle. Up to 90-95% of the yeast cells are recycled, resulting in high cell densities inside the fermenter (10 to 14% wet weight basis/v). It is estimated that yeast biomass increases 5 to 10% (in relation to initial biomass) during a fermentation cycle, which is enough to replace the yeast cells lost during the centrifugation step. Normally, temperature is kept around 32 to 35°C. When fermentation ceases, yeast cells are separated by centrifugation, resulting in a concentrated yeast cell suspension (the yeast "cream") with 60 to 70% (wet weight basis/v) of cells. The yeast cream is diluted with water (1:1), and treated with sulphuric acid (pH 1.8-2.5) for 2 h, in order to reduce bacterial contamination and to be re-used as starter for a next fermentation cycle. After centrifuging, the "beer" or "wine" is driven to distillation for ethanol recovery, normally using distillation tray technology. After distilling a liquid stream called "vinasse" is produced at the ratio of 10-15 liters per liter of produced ethanol. The vinasse can be used as feed replacing soy meal or as irrigation water and fertiliser in cane fields (adding to soil potassium, calcium, magnesium, others micronutrients and some organic matter) (Basso *et al*. 2011).

Figure 17: Fermenters of a sugar cane bioethanol plant, Brazil (© Rutz)

First generation bioethanol can be produced not only from the fermentation of the juice extracted from the stalk of sweet sorghum, but also from the starch in the grains (Figure 18). The process of ethanol production from sweet sorghum grains is similar to that of corn. After washing, crushing and milling the sweet sorghum grains, the starchy material is gelatinised, liquefied and saccharified using α-amylase and gluco-amylase enzymes to produce glucose. Fermentation, distillation and dehydration processing of grain sorghum are similar to those of the sweet sorghum stalk. However, the by-product of grain fermentation is not similar to the one of stalk and it is called DDGS (dried distillers grains with solubles) (Figure 19). DDGS is a solid co-product of the ethanol production process from grain with a high nutrient feed value and is used often by the livestock industry (Almodares and Hadi 2009).

Figure 18: Grain bioethanol plant of ABENGOA in Salamanca, Spain (© Rutz)

Figure 19: DDGS of a grain ethanol plant (© Rutz)

5.3. Second generation bioethanol production (Ligno-cellulosic)

Second generation bioethanol is the ethanol produced from ligno-cellulosic biomass like woody crops, agricultural residues or solid bio-waste (e.g. sorghum bagasse), which often does not cause conflicts between feed/food and industrial uses. Currently, the disadvantage of second generation bioethanol is that it's harder and more expensive to extract the required fuel. The effectiveness of the fermentation of lingo-cellulosic materials presents two principal challenges: The crystalline structure of the cellulose which is highly resistant to hydrolysis, and the ligno-cellulosic association which forms a physical barrier that hinders enzymatic access to the cellulose fibers. Additionally, cellulose acid hydrolysis requires the use of high temperatures and pressures for the destruction of parts of the carbohydrates, which are converted mainly to furanic compounds. Furthermore toxic substances are generated by the partial degradation of lignin (Jacobsen and Wyman 2000).

To make possible the use of lingo-cellulosic materials as feedstocks for the production of ethanol and other chemicals, it is usually necessary to separate their main components (lignin, hemicellulose and cellulose). For this separation, a pretreatment stage is essential, which aims at disorganising the lingo-cellulosic matrix. The pretreatment can be realised through physical, physical-chemical, chemical or biological processes, and can be either associated or followed by hydrolysis procedures of the polysaccharides (hemicellulose and cellulose) in their respective monomeric units - pentoses and hexoses (Betancur and Pereira 2010a, b).

The use of brown-midrib varieties in sorghum has the advantage of producing biomass with lower lignin content, thus enhancing the degradation process. After hydrolysis, the sugars are subject to fermentation in the same way as first generation bioethanol.

The use of biomass sorghum for 2nd generation ethanol production is still not applied at commercial scale today. A general good overview on 2 nd generation biofuels facilities is given e.g. by IEA Task 39 (2013) and Janssen *et al*. (2013).

5.4. Biogas production through anaerobic digestion

The production and utilisation of biogas from anaerobic digestion (AD) provides environmental and socio-economic benefits for the society as a whole as well as for the involved farmers. Utilisation of the internal value chain of biogas production enhances local economic capabilities, safeguards jobs in rural areas and increases regional purchasing power. It improves living standards and contributes to economic and social development (Al Seadi *et al*. 2008).

The process of AD is defined as a biological process in which organic matter is metabolised by a variety of microorganisms in an environment free of dissolved oxygen or its precursors (e.g. H_2O_2).This biological process produces a gas, called biogas, principally composed of methane (CH_4) and carbon dioxide (CO_2). Biogas contains also other gases such as H_2, H_2S and NH_3. The anaerobic digestion process is complex because it involves a diverse group of microorganisms and a series of interdependent metabolic stages.

Figure 20 shows the schematics of the various steps involved in the anaerobic digestion process. The overall process occurs in 4 steps. Complex organic compounds such as proteins, carbohydrates, and lipids are transformed into simple soluble products such as amino acids, sugars, and long-chain fatty acids and glycerine by the action of extracellular enzymes excreted by a group of bacteria called the fermentative bacteria (FB). This first step is commonly known as hydrolysis.

In the second step or acidogenesis the same fermentative bacteria ferment the soluble products of the first step to a mixture of organic acids, hydrogen and carbon dioxide. Acidogenesis is the generation of volatile fatty acids (VFA), such as propionic and butyric acid. These VFA along with ethanol are converted to acetic acid, hydrogen and carbon dioxide by another group of bacteria known as hydrogen-producing acetogenic bacteria (AB). The acetic acid producing step is known as acetogenesis.

Acetic acid, H_2 and CO_2 are the primary substrates for the last step of this process known as methanogenesis. Two groups of microorganisms called archaea are involved in the methanogenesis. The first group which uses the acetate for the generation of methane is known as acetotrophic or acetoclastic methanogens (AM) and the other group generating methane from H_2 and CO_2 are known as the hydrogenotrophic methanogens (HM) (Khanal 2008). On chemical oxygen demand basis, about 72% of methane production comes from the decarboxylation of acetate, while the remainder is from CO_2 reduction (McCarry 1964).

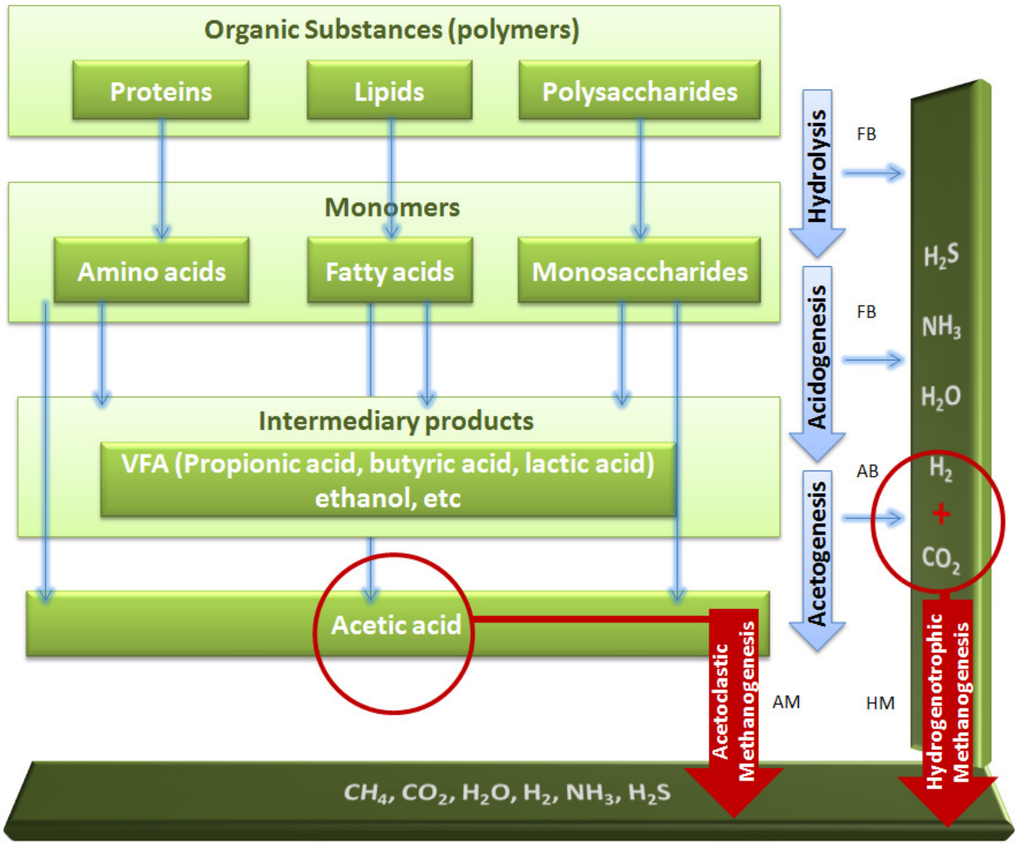


Figure 20: Conversion steps in anaerobic digestion of complex organic matter

The amount of biogas produced depends on the type of feedstock. Sorghum has been reported to be a suitable feedstock for biogas plants (Figure 21) producing mainly methane (Poletti *et al*. 1996; Röhricht 2007). The substrate used can be the silage of whole plant, the bagasse or the stalk.

Similiralry to corn, sorghum can be ensiled without problems. For instance biomass sorghum is used as a feedstock for biogas in Germany. It is being investigated as an alternative or complementary crop to corn. Intensive corn plantation might have a negative effect on abiotic and biotic environmental factors such as soil fertility and biodiversity. Sorghum can particularly reduce the weather-related risk cultivation of corn on very light soils and reclamation areas. On these areas the security of feedstock supply for biogas plants can be increased. Furthermore, it is included in the crop rotation system as the timimg for the seeding is more flexible (Zeise und Fritz 2011).

In order to ensure a good AD process, it is recommended to harvest the crop when the dry matter content is between 28% and 32%. Dry matter contents below 25% and above 35% cause problems with the proper densification of the substrate.

The methane yield of sorghum silage was reported to be 80 m^3/t of fresh feedstock in comparison to the methane yield of corn silage (whole crop) which was 106 m^3/t of fresh feedstock (BMU 2012, Rutz *et al*. 2012), knowing that the methane yield depends on the used variety. For biogas production, the biomass sorghum is chipped during the harvest and then stored as silage until its use. The silage is fed into the digester and during AD process biogas is produced and used for combined heat and power (CHP) production. Alternatively, the biogas can be further upgraded to biomethane and injected as natural gas substitute into the natural gas grid or used directly as transport fuel replacing conventional gasoline and natural gas. In all AD processes, digestate is produced as by-product and used as fertiliser substituting mineral fertiliser. Typical sizes of biogas plants in Europe have a capacity of about 450 kW_{el}. In agricultural biogas plants, the farmer is often the feedstock provider as well as the operator and owner of the plant (Rutz *et al*. 2013).

Aside from methane, high amounts of hydrogen can be produced through anaerobic digestion. Hydrogen has the highest energy content per unit weight of any known fuel (142 kJg), and produces only water when combusted as a fuel or converted to electricity. Thus, hydrogen is considered to be a good energy alternative because of its cleanliness, recycling and efficiency (Das 2009; Gosselink 2002). Among the various possible substrates, carbohydrates are the main source of hydrogen during fermentation processes and therefore the natural biomass rich in carbohydrates, such as the renewable energy crops like sorghum, can be considered as a very promising substrate for bio-hydrogen production (Hallenbeck 2009; Kapdan and Kargi 2006; Antonopoulou *et al.* 2008). Shi *et al*. (2010) reported a cumulative hydrogen yield of 127.26 ml/g for sorghum stalk pretreated by 0.4% NaOH.

Figure 21: Agricultural biogas plant, Germany (© Rutz)

5.5. Combustion of sorghum biomass

The combustion of solid biomass involves a series of different complex chemical and physical processes. Simply represented, biomass combusts with a supply of oxygen, to carbon dioxide and water:

Biomass + oxygen → carbon dioxide + water + energy

The entire combustion process undergoes various phases and can therefore be divided into various combustion stages (Table 6).

The controlled combustion of biomass begins with the heating up phase. In the subsequent drying phase, which takes place at about 100°C, the water adhering to or contained in the biomass is evaporated. Thereby, as is the case in the other combustion stages, the process progresses from the outside towards the inside. As the insides of the fuel particles are still drying out, the pyrolytic decomposition of the biomass components is already beginning from the outside. By the term pyrolysis one understands the thermochemical decomposition of organic material at elevated temperature in the absence of oxygen. This results in a breakdown of the long chain organic bonds into shorter chain connections. Combustible gases in the form of carbon monoxide (CO) and gaseous hydrocarbons as well as pyrolysis oil (tar) are built up. This process does not require any oxygen. As oxygen is present in a chemically stored form or through supplied air, more or fewer complete oxidation reactions come about when heat is released, immediately after the breaking down process.

Table 6: The schematic process of combustion (Hiegl *et al.* 2011)

Phase	Temperature	Product chain
Heating of the fuel through reflection from the flame, fire bed and furnace walls	< 100°C	Air dried wood
Drying of the fuel through evaporation and draining of the water	> 100°C	Air dried wood steam
Pyrolytic decomposition of the water-free fuel	> 150°C	Fuel gas, absolutely dried wood
Gasification of the fuel with oxygen to combustible gases (CO, hydrocarbons) and solid carbon	> 250°C	Fuel gas, wood coal
Gasification of the solid carbon with carbon dioxide, steam and oxygen to carbon monoxide	> 500°C	Fuel gas, wood coal
Oxidation of the combustible gases with oxygen to carbon dioxide and water	700°C – 1,400°C	Exhaust gas, ash
Heat emission of the flame to the surrounding walls, heat exchanger and the newly supplied fuel	< 1,400°C	Exhaust gas, ash

In order to control the process of degassing in combustion systems, atmospheric oxygen, or so-called primary air, is fed into the combustion system and targeted at the location of the pyrolytic decomposition (e.g. fire bed). The heat required by the incomplete reactions of the pyrolysis products is provided by oxygen. For the reaction of solids and liquids (coal, tar), in comparison to pyrolytic decomposition, notably higher temperatures are necessary, in part above 500°C. With the sub process of oxidation, the gas fuels have already partially spread out in the combustion chamber. Through the targeted supply of atmospheric oxygen (secondary air) in this phase a more or less complete oxidation of the released gaseous products can take place. This results in the generation of carbon dioxide (CO_2) and water.

The degradation of hydrocarbons takes place through the building up of CO as an intermediary product that reacts with CO_2 in a progressing oxidation. In this phase light and heat radiation is emitted and flames are visible. Apart from the oxidation that is indicated by the formation of flames, equally significant for solid biogenic fuels is the flameless combustion that takes place in the final stage of the combustion process. The end product of the pyrolytic decomposition is built up solid carbon (charcoal) in the fire bed, which is first gassed (coal gasification) and then in the subsequent gas phase it is oxidised. The ash remains behind as a combustion residue (Hiegl *et al*. 2011).

The development of controlled thermal conversion processes requires studying the influence of the shape, size and density of particles in the conversion of biomass. In a fast pyrolysis unit, the biomass to be processed usually has a wide range of sizes and shapes. Different particle shapes and sizes result in different surface areas and volumes, which are characteristics that directly affect the phenomena of heat and mass transfer, and oxidation and volatilization rates. Besides, the irregular shape of biomass particles hamper the appropriate functioning of feeders in gasification, combustion and pyrolysis reactors.

Cardoso *et al*. (2013) studied the effect of particle size of sweet sorghum bagasse on the physical properties (density, size, aspect ratio, and roundness distributions) using three size ranges (125-355, 355-500 and 500-850 µm). The results showed that the aspect ratios of the three samples were similar, different particle sizes have similar shapes, the ratio between particle dimensions does not change significantly with decreasing particle size and the smaller the particle size, the higher the roundness value.

Alkali oxides, halides and ash content can be problematic when feedstock is intended for combustion applications because these elements can lead to slagging and fouling of boilers. Solutions for counteracting the alkali content of herbaceous biomass include chemical addition to neutralize alkali, blending high-alkali biomass with low-alkali sources to achieve an acceptable ash-fusion temperature in the resulting mixture, and removal of the alkali content through washing techniques. Washing sorghum biomass (50% moisture content) with tap water at room temperature has the potential to improve the quality of sorghum biomass for combustion to levels close to those found to avoid fouling and slagging of boilers. The significant reduction of potassium and chlorine, together with the inherent low levels of sulphur present in sorghum biomass offer a great potential to use this washing process at a commercial scale. However, the addition of water into the biomass as pre-treatment is of concern because of the energy input required to dry the biomass prior to combustion. Nevertheless, if washed biomass is blended at relatively low concentrations with already dried fuels, drying may not be needed at all as long as total moisture of the fuel is within the acceptable limits for combustion. For these reasons, additional investigation is necessary to build a feasibility study to determine the optimum amount of water necessary to achieve the best sorghum biomass quality while reducing dry matter losses. Furthermore, analysis of leachate after washing is also needed to determine its potential use as fertilizer for a sustainable sorghum feedstock production within a closed-loop system (Carillo *et al*. 2014).

The combustion of biomass results in generation of bioenergy (electricity) and heat. Currently the most practical way of utilising sweet sorghum bagasse seems to be combustion for the production of heat and/or electricity. As a fuel, sweet sorghum bagasse has a heating value of 16 MJ/kg dry matter. Depending on the moisture content of the material, the actual heating value per kg of fresh bagasse ranges from 6.7 MJ at a dry matter content of 47% to 10.1 MJ at a dry matter content of 65%. By using the bagasse as a solid fuel, 160 GJ/ha, equivalent to 4,400 l of heating oil, are gained (Grassi 1992).

Gunnerman *et al*. (1986) mentioned that the variety of sorghum is important in order to produce a fuel product which burns cleanly and efficiently. The variety should have at least 5% extractable sugars by weight, less than 0.75% (dry weight) total nitrogen, and should yield at least five tons (dry weight) of biomass per acre. The nitrogen content of the plant is especially important. The selected plant must be sufficiently low in nitrogen to avoid excessive production of nitrogen oxides during combustion of the final product. The bagasse can be stored in an efficient and cost effective way by transforming them into pellets for future use.

5.6. Co-products

Besides its use for energy purposes, sweet sorghum is also valued for the production of commercial products such as alcohol (potable and industrial grade), syrups (natural and high fructose), glucose (liquid and powder), modified starches, maltodextrins, jaggery, sorbitol and citric acid (downstream products from starch) (CFC-ICRISAT 2004). Malted sorghum can be used as a good alternative for baby weaning foods and for beer production as well as non-alcoholic beverages. Furthermore due to its fiber content, sorghum can be used for bedding, roofing, fencing, chewing and it has proven to be suitable for the use in the paper industry according to Sundara and Marimuthu (2012).

Bioethanoö can be transformed into a gel fuel. To produce a gel fuel, denatured ethanol is mixed with a thickening agent (cellulose) and water through a very simple technical process, resulting in a combustible gel. The gel fuel is thus renewable and can be locally produced in most countries e.g. Africa. Jellified and/or solidified liquid fuels (kerosene and ethanol) have been in use since World War II, when they were used by soldiers for cooking. Several variations of jellified ethanol have been produced in small volumes in various countries for up-market recreational (camping, barbecue fire-lighting, etc.) and catering applications (Utria 2004). The advantage of fuel gel is that it does not give off smoke or toxic materials.

6. Sustainability of energy sorghum

This chapter addresses social, economic and environmental impacts of selected energy sorghum value chains. The main focus is thereby on different scales of 1st generation ethanol production systems of sweet sorghum in tropical regions of developing countries, as well as of biogas and 2nd generation bioethanol systems of biomass sorghum in temperate regions of developed countries.

6.1. Overview on energy sorghum value chains

Energy sorghum is a promising energy crop in both developed and developing countries. It is suitable for small and large scale cultivation and value chains. The general value chain of energy sorghum production systems is similar to other bio-energy/biomass production systems:

- Crop cultivation
- Harvesting
- Transport
- Milling (only for ethanol production)
- Processing to the fuel
- Direct use or further transport
- End use

A schematic overview of general energy sorghum production and use pathways is shown in Figure 22. The life cycle of energy sorghum includes cultivation, processing, use as well as end-of-life treatment, recycling and final disposal (cradle-to-grave approach). All inputs into and outputs from the system are taken into account including the several by-products obtained.

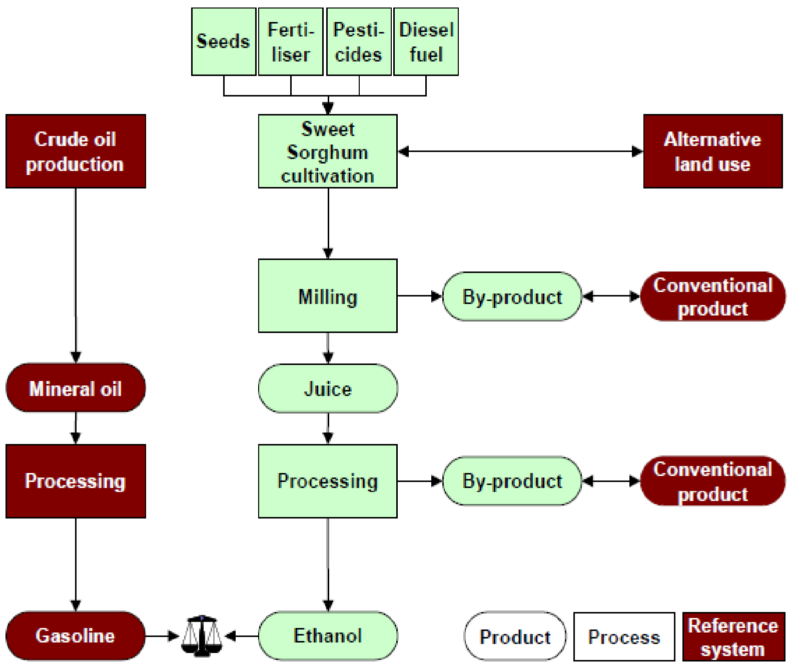


Figure 22: Basic principle of life cycle comparison between sweet sorghum ethanol and gasoline (Braconnier and Reinhardt 2013)

The value chain is characterised by the conversion process and the main and co-products. The conversion technology and the desired products influence the scale of the production system. Thereby, a differentiation between the conversion steps must be made, as the scale is not necessarily the same for the different value chain steps. However, the border between large- and small-scale is fluent. In general small-scale systems describe value chains that involve many individual farmers that provide feedstock for a small ethanol plant, e.g. operated by the farmer's co-operative. A large-scale system is characterised by the involvement of large investors, feedstock cultivation on modern agro-industrial scale, often done by the ethanol plant company itself. The ethanol of large-scale systems is often sold on international commodity markets. The scale of the value chain steps and production systems is important as this largely influences the social, economic and environmental impacts of the system (Rutz and Janssen 2012a). Depending on the perspective of the actors of the value chains this can include positive and negative impacts.

Finally, the application of conversion technologies is influenced by the climatic conditions under which sweet sorghum is cultivated as well as by the status of development of the country. In tropical climates the sugar productivity of sweet sorghum is very high and thus, small to large-scale 1st generation ethanol production systems are suitable. In temperate regions, the sugar content is less, but the productivity of the biomass is high. Therefore sweet sorghum is currently used there for biogas production. The production of second generation biofuels is still not realised at a fully commercial scale today. In general, production of second generation biofuels is more suitable for temperate regions under the current framework conditions due to the high investment needs. The following parameters characterise the agricultural and conversion systems of the sweet sorghum ethanol chain having a large impact on sustainability issues (Rutz and Janssen 2012b):

- Scale of the system: small, medium, large-scale
- Actors of the cultivation system: farmers, industrial farming
- Actors of the production system: villagers, centralised ethanol plant
- Business relationships between the actors: out-grower model, cooperatives, contracted workers
- Economy of the country: emerging country, developing country

6.1.1 Tropical production systems

The sustainability of the cultivation and conversion of sweet sorghum in sub-tropical and tropical climate is affected by various factors. Since many potential cultivation areas of these climate regions are either in developing or emerging countries, socio-economic impacts, negative or positive, are of very high importance. Thereby, "tropical regions" and "developing countries" are no synonyms, of course, but these climatic regions are especially prone to impacts of climate change which may affect the poorest people, namely small-scale and subsistence farmers in developing countries.

A focus of the sweet sorghum value chains in subtropical and tropical climates for energy production is on the production of 1st generation ethanol. The following list shows production scenarios for 1st generation ethanol:

- **Centralised ethanol production system** (small-scale and large scale feedstock production for a large-scale ethanol plant). Merely the cultivation and harvesting of sweet sorghum is performed at village level. After harvest, the sweet sorghum stalks are transported from the villages to centralised ethanol facilities.

- **Decentralised syrup production system** (small-scale feedstock and syrup production for a large-scale ethanol plant). In addition to the cultivation and harvesting of sweet sorghum, also the production of syrup from sweet sorghum juice is performed at village level. The syrup is then transported from the villages to centralised ethanol facilities. This system holds advantages if the infrastructure for biomass transportation to large centralised production units is insufficient or not existent and it provides enhanced value creation at village level. A schematic overview of the decentralised syrup production system is presented in Figure 23.

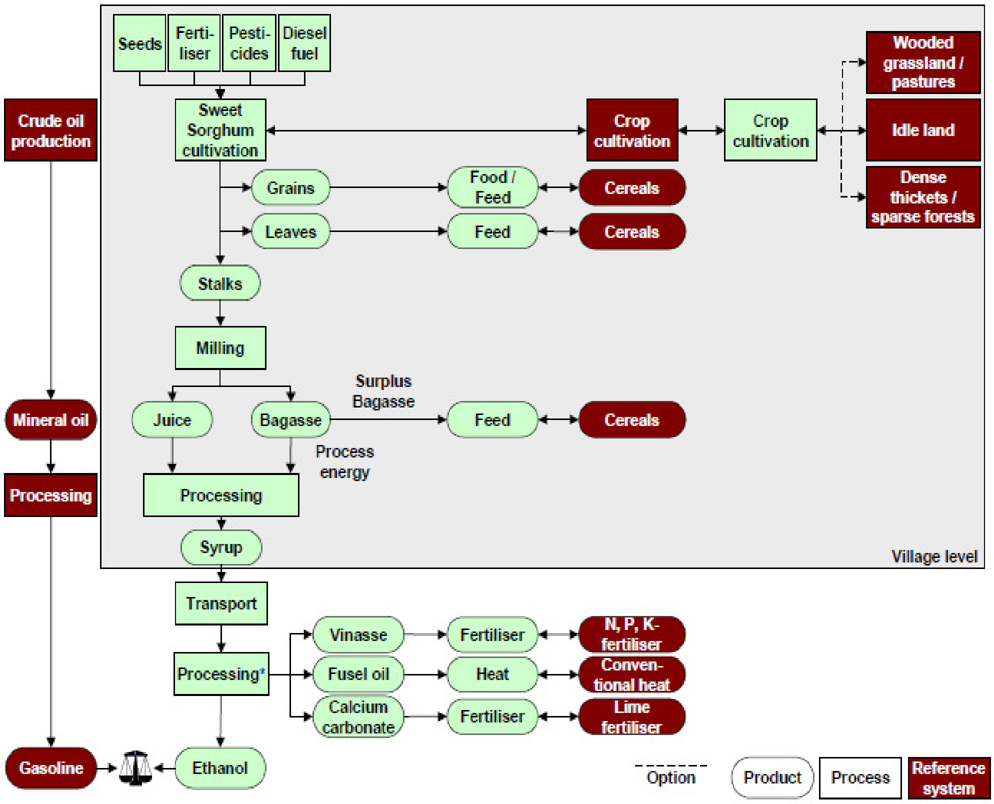


Figure 23: Decentralised syrup production system (Braconnier and Reinhardt 2013)

- **Decentralised ethanol production system** (small-scale feedstock, syrup and ethanol production). In this system, the whole production chain is realised at village level, namely the cultivation and harvesting of sweet sorghum, the milling of the stalks to produce juice, and the processing of the juice into ethanol. Thereby, this system provides maximum value creation and benefit at village level.

6.1.2 Temperate production systems

The production systems in temperate regions are different to those in tropical regions, as the sugar content of the crop is lower and often too low for sugar extraction and processing to 1st generation ethanol. However, biomass sorghum is a good feedstock for biogas production as the high content of sugars, compared to other crops, makes it very digestible (Rutz *et al.* 2013).

For the biogas production, biomass sorghum is crushed after harvest. The biogas is used for heat and power production replacing conventional heat and power or as transport fuel replacing conventional gasoline and natural gas. In all processes, digestate is produced as by-product. It is used as fertiliser replacing mineral fertiliser. A schematic overview of the biogas production system is presented in Figure 24.

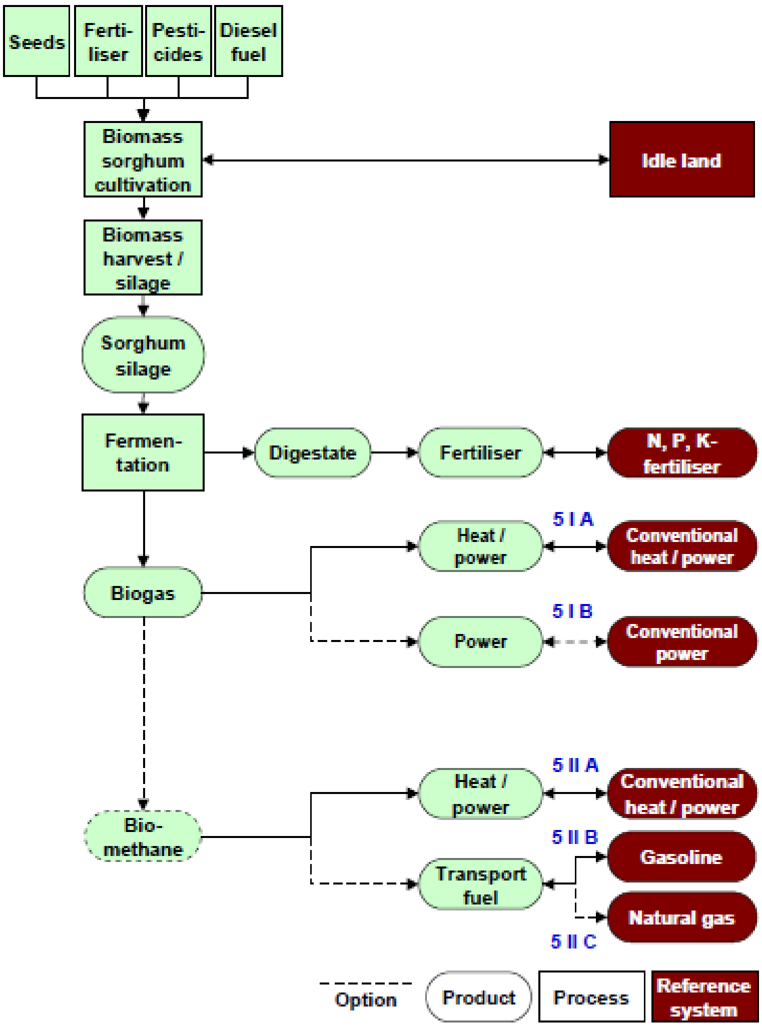


Figure 24: Biogas production system (Braconnier and Reinhardt 2013)

A future option would be to use biomass sorghum for second generation biofuels either for thermo-chemical or biological conversion. However, this is not yet commercially applied. Therefore, it is challenging to discuss about its impacts, especially as the cost of the production are difficult to predict. A schematic overview of the ligno-cellulose-ethanol production system is presented in Figure 25.

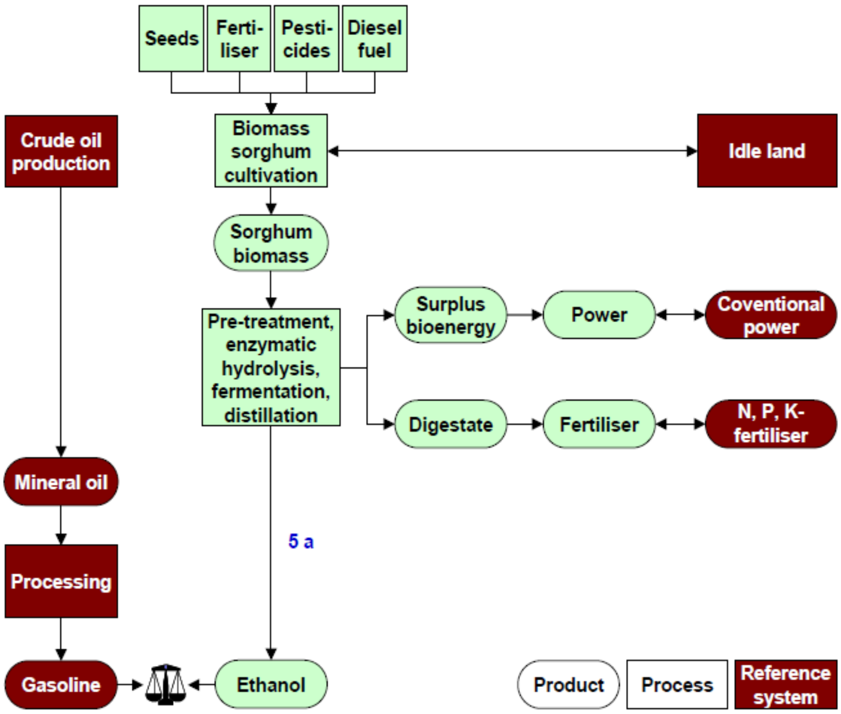


Figure 25: Second generation ethanol production from biomass sorghum ligno-cellulose for temperate climates (Braconnier and Reinhardt 2013)

6.2. Economic impacts

Three of the most important criteria for economic sustainability are profitability (the price of the biofuel exceeds the production costs), equity (distribution of benefits or value added among actors along a biomass-biofuel value chain or across generations) and efficiency (the maximum amount of yield is obtained with a given quantity of resources). The imperative of sustainability requires that we clearly consider these criteria in both the short and long term. Hence, from the perspective of sustainability, the first objective is to ensure the long-term economic viability of the productive system.

6.2.1 Economic profitability and equity

The first criterion for long-term viability of a production system utilising resources to produce a marketable output is that it shows economic profitability: producers will only be willing to pursue biofuel production if it is economically profitable. Key factors that can affect profitability include alternative competitive uses of the feedstocks and energy prices. Alternative uses of the feedstock play an important role in the decision making process of producers. If prices for biofuels fall below the prices of other possible end-products (food, feed, timber, etc.) it would be more profitable to cultivate these products than to derive fuel out of the feedstock. Accordingly, their prices determine the price floor for biofuels. To be profitable and competitive with fossil fuels, biofuel production costs have to stay below the price of the oil equivalent. Therefore, oil prices set a price ceiling for the price of biofuels. If costs exceed this value, the biofuels will be automatically priced out of the market (Schmidhuber, 2007). Estimated biofuel production costs show significant differences depending on factors such as scale of the plant, technology complexity, energy sources and feedstock costs (Elbehri *et al.* 2013).

Currently, in Brazil bioethanol is considered economically competitive compared with oil which is still not the case in other parts of the world.

Selected impacts on profit generation of energy sorghum in tropical and temperate regions are presented in Table 7 and Table 8.

Table 7: Impacts on profits of energy sorghum in large- and small-scale 1st generation ethanol production systems in tropical regions (Rutz *et al.* 2013)

Large-scale cultivation and large-scale conversion	Since smallholders are not involved, there is no revenue generation for local farmers unless contract agriculture can be established. The revenues for the plant operators are generally larger in larger plants. Due to the higher efficiency and economies of scale, the quality of the products may be better and the prices of the end product lower.
Small-scale cultivation and large-scale conversion	Depending on the contracts, small farmers may have the security that the plant operator buys their feedstock, thus generating a stable income. However, the sale of the stalks depends on the centralised ethanol plant which is buying the stalks. If only few local mills exist, farmers have no influence on the stalk prices and are thus vulnerable.
Small-scale cultivation and small-scale conversion	A longer value chain for ethanol production on smaller scale generates more local revenues in comparison to the sale of only stalks or syrup. Small-scale farmers can themselves decide if ethanol is sold to external markets or also used for local consumption e.g. for cooking. Thus, access to modern energy is increased.

Table 8: Impacts on profits of energy sorghum in biogas and 2nd generation biofuels production facilities in temperate regions (Rutz *et al.* 2013)

Biogas production	Biogas plants are much smaller than second generation biofuels plants. Thus, more people (farmers) profit from higher revenues, especially as usually the feedstock producer is at the same time the plant operator. However, the revenues depend on public support schemes. The use of biomass sorghum instead of other crops does not have a real impact on the profits.
2nd generation biofuels	The profits are quite uncertain as today no real commercial 2nd biofuels plants exist. The use of biomass sorghum instead of other crops does not have a real impact on the profits.

6.2.2 Efficiency of the whole process

The efficiency of the value chain depends especially on the scale of the single production steps, as well as on climatic conditions and the agricultural and industrial practices. Overall efficiencies are comparable to ethanol from sugar cane or sugar beet, although they may be a little lower (Vecchiet 2010).

Selected impacts on the efficiency of the value chains in tropical and temperate regions are presented in Table 9 and Table 10.

Table 9: Impacts on the efficiency of sweet sorghum value chains in large- and small-scale 1st generation ethanol production systems in tropical regions (Rutz *et al*. 2013)

Large-scale cultivation and large-scale conversion	The large-scale cultivation and conversion of sweet sorghum increases the overall efficiency of the value chain. This is due to scales effects and due to the general higher investments. Furthermore, access to improved seeds, input materials and technology is generally available. Harvesting can be done with efficient machinery. The conversion process is usually efficient, especially for new and modern plants.
Small-scale cultivation and large-scale conversion	Small-scale farmers can benefit from improved input material such as seeds, pesticides, fertilisers, etc. from the large-scale ethanol plant. This increases the overall efficiency of the agricultural production. As the ethanol production is on large-scale, the efficiency is generally higher. However, small farmers may be vulnerable to dependencies on improved seeds provided by the large-scale ethanol plant. The large-scale ethanol plant may also provide training for the farmers
Small-scale cultivation and small-scale conversion	Farmers are often not trained in best agricultural practices to increase yields. If not properly trained e.g. on the application of pesticides, negative environmental and human health impacts may occur and efficiency is reduced. Furthermore, access to improved sweet sorghum varieties may be limited for small scale farmers. Small farmers are vulnerable to dependencies on improved seeds (e.g. hybrid and GMO seeds). Sweet sorghum cultivation and ethanol production on small-scale is usually less efficient than on larger scales.

Table 10: Impacts on the efficiency of biomass sorghum value chains in biogas and 2nd generation biofuels production facilities in temperate regions (Rutz *et al*. 2013)

Biogas production	Land use efficiency of biogas (biomethane) from biomass sorghum is higher than of other 1st generation biofuels (e.g. biodiesel from rapeseed or ethanol from sugar beet), especially in the transport sector. If biogas is used in a CHP unit to produce electricity, the “waste heat” should be also used. This is currently a bottleneck in several European biogas plants.
2nd generation biofuels	Real data on the efficiency of 2nd generation biofuels are hardly available, especially if biomass sorghum is considered as feedstock.

6.2.3 Investment needs for the system set-up and for the operation

Energy sorghum can be cultivated with very low financial resources. Farmers need agricultural land and seeds to grow the crop. The plant can be easily reproduced by seeds. However, good productivity and efficiency of the cultivation needs input such as human work, energy, fertilisers, and pesticides, and thus requires financial resources.

Even if the feedstock production can be done at very low cost, considerable financial resources are needed for the further processing steps, such as transport, milling and conversion to ethanol. In general it can be said that the larger the system is, the larger are the financial resources. However, the availability of financial resources is often a key limiting factor, especially in developing countries. Table 11 shows selected impacts of sweet sorghum value chains in tropical climate.

Table 11: Impacts on investments of sweet sorghum in large- and small-scale 1st generation ethanol production systems in tropical regions (Rutz *et al.* 2013)

Large-scale cultivation and large-scale conversion	Large facilities need large investments. Investors in developing countries that are interested in ethanol production are very limited. If investors from foreign countries intend to invest in large-scale ethanol systems, they are likely to be named as “landgrabbers”. The political instability and lack of suitable infrastructure makes investments often risky.
Small-scale cultivation and large-scale conversion	Models exist where the ethanol plant operator provides resources for an efficient cultivation of the feedstock by the small farmers. However, these arrangements may not be done in a fair way, as the involved parties are often not at eye level.
Small-scale cultivation and small-scale conversion	Access to agricultural input (fertiliser, pesticide) is expensive and limited for small scale farmers. Equipment for ethanol production (presses, distilleries) may be too expensive for small-scale producers. Harvesting machinery for sweet sorghum may be too expensive.

6.3. Social impacts

The social dimension of biofuel sustainability relates to the potential for rural development, poverty reduction and inclusive growth. The social (or socio-institutional) dimension of biofuel sustainability can touch on many potentially interlinked issues. This raises a number of methodological difficulties including the challenge of distinguishing between direct and indirect social issues. In this section, we focus on the following aspects of social sustainability: land ownership rights, job creation, health and working conditions, contribution to rural development and national revenues and public acceptance and acceptance of the involved stakeholders. All these issues more or less tackle a common goal – the need to integrate small-scale farmers within biofuel development and ensure inclusive benefit sharing, safeguarding of basic rights and local means of livelihood consequent to the introduction of biofuels.

6.3.1. Food and energy security

In comparison with current sugar and starch crops for bio-ethanol production, energy sorghum offers important benefits with respect to food security as it can serve as multiple purpose crop for food, feed and fuel at the same time. Its seeds are valuable cereals and the leaves are high-value feed, thus contributing significantly to enhancing food supply and improving food security, especially in rural areas of developing countries that are prone to food insecurity. In addition to the grain used for human or animal consumption, sweet sorghum accumulates sugars with little competition between grain and sugar production. The bagasse can be used as animal feed and it is reported to have a better nutritional value than the bagasse of sugar cane (Almodares and Hadi, 2009).

The production of bio-ethanol based on traditional food crops may lead to increases of agricultural commodity prices which negatively affect access to food, particularly in net food importing developing countries and for the poorest therein. Significant price increases have already occurred in major bio-ethanol feedstock markets such as corn and sugar.

According to the Food and Agriculture Organisation of the United Nations, food security is influenced by four main aspects: availability, access, stability and utilisation (FAO, 2007). Thereby, food availability can be threatened by bio-ethanol production through competition with food production over land, water and other productive resources. This resource competition concerns present sugar and starch feedstock and will be reduced for 2nd generation technologies based on ligno-cellulosic biomass. Access to food (the ability of households to buy food) is affected if food prices rise faster than real incomes, leading to food insecurity.

Finally, sweet sorghum can be associated with existing agricultural (e.g. sugar cane) systems, thereby increasing (energy, food and feed) productivity and leading to a revitalisation of agricultural production which is currently suffering from low investment and low productivity, especially in rural areas of developing countries (Janssen *et al.* 2009).

Some selected impacts of sweet sorghum in large- and small-scale 1st generation ethanol production systems in tropical regions on food and energy security are presented in Table 12.

Table 12: Impacts of sweet sorghum in large- and small-scale 1st generation ethanol production systems in tropical regions on food and energy security (Rutz *et al.* 2013)

Large-scale cultivation and large-scale conversion	Large scale systems may contribute to regional development which penetrates to the poorest of the region and it could thus lead to increased food access. On the other hand, if the local population is not benefitting from the large-scale production system, there is the risk that food access and also availability in the region is reduced.
Small-scale cultivation and large-scale conversion	Farmers could generally also benefit from increasing food prices, as their income from sweet sorghum cultivation is higher. This applies only if the ethanol plant forwards the high prices to the farmers.
Small-scale cultivation and small-scale conversion	The cultivation of sweet sorghum may increase the income of small farmers, thus leading to increased food access. Farmers could generally also benefit from increasing food prices, as their income from sweet sorghum cultivation is higher. Sweet sorghum enriches the diversity of agricultural products of small farmers, thus reducing risks if only one or few crops are cultivated. Sweet sorghum is edible and can be used as multi-purpose crop for own consumption, which is not possible for other (toxic) crops like Jatropha.

6.3.2. Land ownership rights

Climate change and expanding biofuel production are likely to lead to greater competition for access to land. This increased competition poses a threat to the livelihoods of the millions of farmers, pastoralists, fisherfolk and forest dwellers living in areas with no formal land tenure rights. Sound land tenure policies and planning will be crucial. Given that land is a limited resource, the appropriate use of land depends on the value it can provide to those who hold rights over it. The value can be measured in many ways – e.g. wealth generation, conservation and ecosystem servicing. Biofuels are believed to offer commercial opportunities to enhance the contribution of land to individuals, groups and governments. Access to land (usage or ownership) depends on the decisions of those who hold rights over the land. Those rights may relate to entitlement of ownership or use (e.g. grazing, water) and may be based on national legislation, customary law or combinations of both. In reality, land rights and the processes to gain access to land are often unclear. Many governments have expressed hope that the development of energy crops may open up the possibility of using unproductive land. However, acquisition of land, even if not currently under crop production, can pose problems if rural communities who may have historical claims to the land for collecting fuelwood or for grazing are unable to protect those claims because they are based on common law and informal tenure systems. As a result, there is a risk that expansion of energy crops may lead to the ouster of vulnerable groups or owners without former documentation. This is all the more likely under governmental decrees or from higher land prices (rent or sale) whereby the poor are generally squeezed out of the market. There is also the potential negative effect of land speculation, by simply acquiring land for biofuels. Such speculation, if not controlled and regulated, can create hardships for small farmers and for agriculture in general. Such indirect impacts might occur on a local, national or – through international trade – even global level (Elbehri *et al*. 2013).

6.3.3. Job creation, health and working conditions

In general, the production of biofuels generates more employment opportunities and jobs than the production of fossil fuels, as the processing takes place on a smaller scale and involves more stakeholders. This also applies to the use of energy sorghum for bioenergy production. The example of an ethanol plant using sweet sorghum in Uganda shows that up to 250 jobs were expected to be created in Kayunga District for the operation of an ethanol plant with 20 million litres ethanol output per year (Muzaale 2011; Uganda Investment Forum 2013). However, it has to be recognised that these are expected figures; real data were not available to the authors. In addition to the direct workers at the facility, 6,000 farmers have been given sweet sorghum seeds to plant sweet sorghum (Muzaale 2011).

Besides the potential to generate jobs, health issues and working conditions must be considered, especially in developing countries. However, this applies to any business, independently if biofuels or other sectors are considered. It is in general not expected that the cultivation and processing of energy sorghum has larger negative impacts on health issues and working conditions than the cultivation and processing of other crops. Selected impacts of sweet sorghum on job creation, health and working conditions in tropical and temperate regions are presented in Table 13 and Table 14.

Table 13: Impacts of large- and small-scale 1st generation ethanol production systems from sweet sorghum on job creation, health and working conditions in tropical regions (Rutz *et al*. 2013)

Large-scale cultivation and large-scale conversion	In centralised systems (with mechanical harvesting technologies) fewer workers may be needed, thus less job opportunities are created. Mechanical harvesting avoids hard and dangerous work. Larger companies must on the one hand comply to stricter rules on health and on working conditions, this is, however, often not implemented, especially in developing countries.
Small-scale cultivation and large-scale conversion	In the crop cultivation step more workers are needed than in the large-scale system. In the conversion step only slightly more workers are needed (due to more administration to deal with many smallholders).
Small-scale cultivation and small-scale conversion	Due to general lower mechanisation rates of the conversion process, more employment is generated per litre ethanol than in larger systems. Ethanol production at small-scale level not only creates direct employment in the value chain, but also indirect employment through related microenterprises. Smaller farmers can influence their working conditions.

Table 14: Impacts of biogas and 2nd generation biofuels production from biomass sorghum on job creation, health and working conditions in temperate regions (Rutz *et al.* 2013)

Biogas production	The cultivation of biomass sorghum for biogas production has not per se any impacts on jobs creation in comparison to other crops for biogas production. However, due to the smaller scale of biogas systems, in comparison to 2nd generation biofuels systems, biogas production generates generally more job opportunities compared to 2nd generation biofuels. Rules on health safety and working conditions are usually implemented in most developed countries.
2nd generation biofuels	As the whole value chain is on a very large-scale, fewer jobs may be generated than in smaller systems. Rules on health safety and working conditions are usually implemented in most developed countries.

6.3.4. Public acceptance and acceptance of the involved stakeholders

Public acceptance is a prerequisite for the development of biofuels. The public perception largely depends on cultural aspects, history and economy of the producing countries, objectives of importing countries, environmental and social targets, as well as on the positive or negative impacts on individuals and communities. The use of energy sorghum is so far not very much under public debate, as its use for bioenergy is currently still small. Furthermore, besides the public acceptance, also the acceptance of the crop by biofuel market actors is needed. The use of energy sorghum for bioenergy is still new and has little application in comparison to e.g. soy, corn and sugar cane. Thus some farmers that had no experience with energy sorghum so far may hesitate to cultivate this crop.

Selected impacts on the public acceptance and acceptance of the involved stakeholders of energy sorghum value chains in tropical and temperate regions are presented in Table 15 and Table 16.

Table 15: Public acceptance and acceptance of the involved stakeholders of sweet sorghum in large- and small-scale 1st generation ethanol production systems in tropical regions (Rutz *et al.* 2013)

Large-scale cultivation and large-scale conversion	At local level the public acceptance of large-scale production systems depends largely on the associated benefits of the local people. If the project is accompanied by sustainable investments in infrastructure, the acceptance is higher. At the international level, ethanol from sweet sorghum was not yet widely mentioned in the media, due to the currently low use of sweet sorghum for ethanol.
Small-scale cultivation and large-scale conversion	The public acceptance mainly depends on the conditions offered by large ethanol plants to the farmers. Manual harvesting of sorghum causes itching. Therefore, farmers often hesitate to cultivate sweet sorghum.
Small-scale cultivation and small-scale conversion	The public acceptance of smaller systems is generally high, as long as the system is operational and as long as all involved stakeholders benefit from it. The cultivation of sweet sorghum for ethanol production may be relatively new to many farmers, so that awareness campaigns and training is needed. Manual harvesting of sorghum causes itching. Therefore, farmers often hesitate to cultivate sweet sorghum.

Table 16: Public acceptance and acceptance of the involved stakeholders of biomass sorghum in biogas and 2nd generation biofuels production facilities in temperate regions (Rutz *et al.* 2013)

Biogas production	The extension of corn cultivation for biogas production (e.g. in Germany) has led to public protests in areas with high corn density. As biomass sorghum looks similar to corn, the public acceptance of biomass sorghum in these areas may be reduced, due to the negative perception on corn. The acceptance of biomass sorghum as energy crop by farmers depends on their experiences with the crop. Especially in temperate regions, biomass sorghum is a relatively new crop for biogas production.
2nd generation biofuels	If second generation will become commercial, people may wonder why biomass sorghum, an annual crop, should be used for the production of 2nd generation biofuels instead of woody plants and residues. The use of bagasse from biomass sorghum would be good, but will be hardly available in temperate regions in the near future. It is not clear if biomass sorghum will be furthermore be accepted by plant operators of 2nd generation biofuel plants, as experience is low. Especially for 2nd generation ethanol plants, it is difficult to switch from one feedstock to another, as the biological fermentation conditions have to be modified.

6.4. Environmental impacts

The most important environmental impacts to be considered for the production of bioethanol from energy sorghum are the energy balance, GHG and other pollutants emissions, direct and indirect land use, biodiversity, water use for agriculture (bioenergy) and water footprint and preservation of soil productive capacity.

6.4.1. Energy balance

The contribution of any biofuel to energy supply depends both on the energy content of the biofuel and on the fossil energy going into its production. This includes energy required to cultivate (fertilisers, pesticides, irrigation technology, tillage) and harvest the feedstock, to process the feedstock into biofuel, and to transport the feedstock and the resulting biofuel through the various phases of production and distribution. Fossil energy balance, defined as the ratio between renewable energy output of the resultant biofuel and fossil energy input needed in its production, is a crucial factor in judging the desirability of biomass-derived biofuel: this concept measures to what extent biomass is qualified to replace fossil fuels. An energy balance of 1.0 indicates that the energy requirement for the bioenergy production is equal to the energy it contains (Armstrong *et al*. 2002). A fossil fuel energy balance of 2.0 means that a litre of biofuel contains twice the amount of energy as was required for its production (Elbehri *et al.* 2013).

Variations in the estimated fossil energy balances across energy sorghum and fuels differ greatly with specific scenarios and local conditions. In general, the results depend on factors such as feedstock productivity, production location, agricultural practices, land-use changes, the use of by-products (e.g., bagasse), type and efficiency of conversion technologies and the type of fossil energy carriers that are replaced (Elbehri *et al*. 2013).

Various studies have investigated the energy balance of sweet sorghum for ethanol production grown under different scenarios and local conditions. Worley *et al*. (1992)

indicated that it is profitable, from an energy standpoint, to produce liquid fuel from sweet sorghum. The improved energy ratio for sweet sorghum indicates that, as the price of liquid fuel rises with all other variables held constant, sweet sorghum will gain an economic advantage. An average energy output to input ratio of 2.83 for sweet sorghum across seven site-years in Nebraska USA was reported by Reed *et al.* (1986). The energy balance calculated by Wortmann *et al*. (2008) was 3.63 compared to grain sorghum (1.50) and corn (1.53).

Rao Dayakar *et al.* (2004) also reported that sweet sorghum has high net energy balance. Even though the ethanol yield per unit weight of feedstock was lower for sweet sorghum compared to sugarcane, the much lower production costs and water requirement for this crop more than compensates and hence, sweet sorghum still ends up with a competitive cost advantage in the production of ethanol in India.

All the previously stated studies undergone in different conditions show that bioethanol production from sweet sorghum has a positive net energy balance, which can contribute significantly to the conservation of fossil resources and to the mitigation of greenhouse gases. If the crop is used for the production of ethanol (from grains and sugar) and green electricity (from surplus bagasse), 3,500 litres crude oil equivalents can be saved per hectare cultivation area. If both food from grains and ethanol from the juice are produced, 2,300 litres crude oil equivalents can be saved per hectare cultivated area. Even if the seeds were used as food, bioethanol from the stem's sugar juice still shows clear advantages to fossil fuels. If both sugar and seeds were used as food, the respective conversion related energy and greenhouse gas expenditures could be compensated by producing second generation ethanol from the bagasse (Srinivasa Rao *et al.* 2009).

6.4.2. Greenhouse gas emissions and other air pollutants

Tackling global warming and the possibility of reducing GHG emissions is a main driver for biofuel development. The negative effects of GHG emissions on climate have been known for a long time. GHG emission assessments typically include those of CO_2, methane (CH_4), nitrous oxide (N_2O) and halocarbons. The gases are released during the whole product life-cycle of the biofuel depending on the agricultural practices (including fertiliser use, pesticides, harvesting, etc.), the conversion and distribution process, and the final consumption and use of by-products. Concerns about climate change and the need to reduce GHG emissions have become increasingly important in continuing policy support for biofuels. The biofuel industry is therefore increasingly required to demonstrate that the net effect is lower GHGs when taken across the whole lifecycle, from crops to cars. While plants absorb CO_2 from the atmosphere when they are growing, which can offset the CO_2 produced when fuel is burned, CO_2 is also emitted at other points in the process of producing biofuels.

First- and second-generation bioethanol from energy sorghum contributes significantly to mitigation of greenhouse gases: between 1.4 and 22 kg carbon dioxide equivalents can be saved depending on yield per cultivation area, production method, type and efficiency of conversion technology, use of by-products such as bagasse, land cover prior to sorghum cultivation, and land use changes (Elbehri *et al*. 2013).

Nitrification and denitrification are the primary sources of nitrous oxide (N_2O) production and emissions from agricultural systems and contribute significantly to global warming. Blocking the function of nitrifying bacteria or slowing the nitrifiers' function (i.e. reducing the nitrification rates) can significantly reduce nitrogen losses associated with nitrification and extend the persistence of nitrogen as ammonium in the soil for uptake by plants. This can lead to improved nitrogen recovery and use efficiency in agricultural systems. Recently, it was shown that some plant species have the ability to release nitrification inhibitors from roots that suppress nitrifiers' function, a phenomenon termed 'biological nitrification inhibition' (BNI) (Subbarao *et al*. 2006; 2009b). The preliminary field studies indicate the potential for wild sorghum species. such as *S. arundinaceum* acting as a genetic source for high-BNI capacity. The BNI function in sorghum thus, could become a critical trait targeted for genetic improvement, as part of an integrated strategy towards development of sorghum varieties with adequate BNI capacity to suppress soil nitrification and utilise nitrogen in NH^{4+} form (Subbarao *et al*. 2009a). Preliminary studies indicate that sweet sorghums have BNI capacity similar to that of grain sorghums, indicating that BNI function can be amenable for genetic improvements/manipulation to reduce N_2O emissions and improve nitrogen use efficiency in sweet sorghums (Srinivasa Rao *et al*. 2009).

6.4.3. Land use change (LUC)

Land use is the human use of land which involves the management and modification of natural environment or wilderness into built environment such as fields, pastures, and settlements (Watson *et al*. 2000). Land use change (LUC) is the change from used land from one use to another use. Often, land use change is also referred to the change of non-used land (virgin land, abandoned land, degraded land) to another use.

Table 17: Land use impacts of sweet sorghum use in large- and small-scale 1st generation ethanol production systems in tropical regions (Rutz *et al*. 2013)

Large-scale cultivation and large-scale conversion	If centralised ethanol plants set-up own large-scale sweet sorghum plantations in developing countries, this may happen by negatively affecting the poor (land grabbing). There is a risk of displacement and marginalisation of local communities and smallholders. There is a higher risk that sweet sorghum is cultivated in monocultures with negative environmental (e.g. soil fertility, soil compaction, deforestation) and socio-economic (ecosystem services) impacts. The land use competition may be high, as larger plants usually select good quality agricultural land. The land use efficiency (t / ha) and overall process efficiency of these systems may be higher.
Small-scale cultivation and large-scale conversion	Existing agricultural structures and sizes of farms can be maintained. Due to the smaller structures of these systems the (bio)diversity and ecosystem services may be larger. The land use efficiency of these systems may be lower than for large-scale cultivation, but larger ethanol facilities may support smaller farmers, e.g. through training or agricultural equipment.
Small-scale cultivation and small-scale conversion	Existing agricultural structures and sizes of farms can be maintained. Due to the smaller structures of these systems the biodiversity and ecosystem services may be larger. The land use efficiency of these systems is generally lower due to lack of resources and knowledge. This may be partly compensated if good cooperative structures exist. Sweet sorghum cultivation systems can be easily integrated into existing small-scale agricultural structures without negatively affecting small farmers and villagers (no land grabbing). Villagers are themselves responsible for suitable land use and production practices. They are not forced by large companies to adapt to their rules.

Thereby distinction is made between direct land use change and indirect land use change. Direct land use change (dLUC) is referred to the change of a specific land area that is directly converted from one status to another status. In the biofuels sector, dLUC is referred to the production of biofuel feedstock that is produced on land directly converted from another status to agricultural land for feedstock production (EC 2010). If the feedstock for biofuels or bio-products is instead cultivated on existing agricultural land, it may then displace other crop production some of which ultimately may lead to the conversion of land into agricultural land. Through this route, the extra biofuel demand can lead indirectly to land use change, from which the term indirect land use change (iLUC) is derived (EC 2010). This indirect effect manifests itself through a change in demand for agricultural commodities, and their substitutes, in global markets.

A major advantage of energy sorghum compared to other crops is that it can grow under harsher conditions. It can still be well cultivated on marginal soils with a wide range of pH, salinity, and soil structure that are unsuitable for food production, although the productivity may be reduced on these lands. Selected land use impacts of sweet sorghum and biomass value chains in tropical and temperate regions are presented in Table 17 and Table 18.

Table 18: Land use impacts of biomass sorghum use in biogas and 2nd generation biofuels production facilities in temperate regions (Rutz *et al.* 2013)

Biogas production	Sweet sorghum is generally a good alternative to other crops for biogas production, especially to corn. Thus it broadens crop alternatives and crop rotation. However, increased energy crop production for biogas has led in some areas to increased prices for land rental.
2nd generation biofuels	Biomass sorghum is an annual crop, thus for 2nd generation biofuels production woody crops or residues may be preferred as impacts on land-use are usually lower for woody crops.

6.4.4. Biodiversity

Biodiversity, defined as the abundance of species (plants, animals and microorganisms) in a habitat, is essential for the performance of an ecosystem. Biomass production for bioenergy can have both positive and negative impacts on biodiversity. When degraded land is used, the diversity of species might be enhanced. Yet, the practices of large energy crop monocultures can be detrimental to local biodiversity, especially through habitat loss, the expansion of invasive species and contamination from fertilisers and herbicides.

On a global scale, biodiversity is essential for the functioning of ecosystems which in turn ensure diverse gene pools and hydrological cycles which enable agriculture. However, on a fieldscale, the most efficient cropping systems have great uniformity and very little biodiversity. The use of plant biomass to provide liquid fuels has the potential to increase agriculture's impact on biodiversity. The extent of habitat loss depends on the type of land-use change. Energy sorghum, known to be able to grow on marginal soils and degraded land with reduced fertilisation make his impact on biodiversity restricted as long as it is cultivated in small scales rotated with other crops (Elbehri *et al.* 2013).

Glossary

1st generation bioethanol	Bioethanol produced from sugar, starch, or vegetable oil
2nd generation bioethanol	Bioethanol produced from sustainable ligno-cellulosic biomass
Acidic soils	Soils with a pH value of less than 6
Active radiation	The spectral range (wave band) of solar radiation from 400 to 700 nanometers that photosynthetic organisms are able to use in the process of photosynthesis. This spectral region corresponds more or less with the range of light visible to the human eye
Aldehyde	An organic compound containing the CHO group at the end of a hydrocarbon chain
Alkaline soils	Soils with a pH value of more than 8
Anchorage	The condition of being secured to a base
Bagasse	The residual lingo-cellulosic cake remaining after crop pressing
Baling	compressing and packaging of raw or finished material tightly forming a bale
Biodiversity	The total variability within and among species of all living organisms and their habitats
Breeding	The art and science of changing the genetics of plants in order to produce desired characteristics
Brix hydrometer	An instrument used to measure the specific gravity (or relative density) of liquids; that is, the ratio of the density of the liquid to the density of water
C4 plant	A plant in which the CO_2 is first fixed into a compound containing four carbon atoms before entering the Calvin cycle of photosynthesis. A C4 plant is better adapted than a C3 plant in an environment with high daytime temperatures, intense sunlight, drought, or nitrogen or CO_2 limitation
Cellobiose	A disaccharide $C_{12}H_{22}O_{11}$ composed of two glucose molecules linked by a $\beta(1\rightarrow4)$ bond and obtained by partial hydrolysis of cellulose - called also cellose
Centrifugation	A process that involves the use of the centrifugal force for the sedimentation of mixtures with a centrifuge
Coagulation	A process that involves the transformation of a liquid into to a gel or solid state by a series of chemical reaction

Cultivar	A plant or grouping of plants selected for desirable characteristics. Cultivar is a general word that includes lines, varieties and hybrids
Degrees Brix (°Bx)	Unit of measurement of sucrose in a liquid
Denitrification	A microbially facilitated process of nitrate reduction (removal) that may ultimately produce nitrogen (N_2) through a series of intermediate gaseous nitrogen oxide products
Drainage	The natural or artificial removal of surface and sub-surface water from an area
Evapotranspiration	The process by which water is transferred from the earth to the atmosphere by evaporation of water and transpiration from plants
Frothing	The process of producing bubbles and foam in or on a liquid
Furanic compounds	Compounds of Furan, a heterocyclic organic compound colorless, flammable and highly volatile. It is toxic and may be carcinogenic
Fusel oil	An acrid, oily, poisonous liquid mixture of amyl alcohols, occurring in incompletely distilled alcoholic liquids
Genetic Diversity	The genetic variation present in a population or species
Genotype	The entire set of genes in an organism
Germplasm	A set of genotypes that may be conserved or used, e.g. seeds, clones, pollen
Glucanase	Enzymes that break down a glucan, a polysaccharide made of several glucose sub-units. As they perform hydrolysis of the glucosidic bond, they are hydrolases
Glucosidase	Enzymes that catalyse the hydrolysis of the glycosidic linkage to release smaller sugars. They are extremely common enzymes with roles in nature including degradation of biomass such as cellulose and hemicellulose
Hardships	Severe suffering or privation
Hybrid	An offspring resulting from the interbreeding between two parental lines. Usually, hybrids cannot reproduce
Ideotype	A biological model which is expected to perform or behave in a particular manner within a defined environment. It describes the idealised appearance of a plant variety
Invert sugar	A mixture of glucose and fructose. It is obtained by splitting sucrose into these two components. Compared with its precursor, sucrose, inverted sugar is sweeter and its products tend to retain moisture and are less prone to crystallisation

Jaggery	A traditional uncentrifuged sugar. It is a concentrated product of date, cane juice, or palm sap without separation of the molasses and crystals
Ketone	A compound containing a carbonyl functional group bridging two groups of atoms. The general formula for a ketone is RC(=O)R' where R and R' are alkyl or aryl groups
Lignin	Organic substance which act as a binder for the cellulose fibres in wood and certain plants and adds strength and stiffness to the cell walls. The chemical structure of lignin is composed of a complex polymer of phenylpropanoid subunits, laid down in the walls of plant cells such as xylem vessels and sclerenchyma
Ligno-cellulose	carbohydrate polymers (cellulose, hemicellulose), and an aromatic polymer (lignin). These carbohydrate polymers contain different sugar monomers (six and five carbon sugars) and they are tightly bound to lignin
Line	Breeding material which tends to be genetically identical
Maltodextrins	An oligosaccharide produced from starch by partial hydrolysis
Midrib	The central vein of a leaf
Monsoon	Seasonal changes in atmospheric circulation and precipitation associated with the asymmetric heating of land and sea.
Nematode	Unsegmented worm of the phylum Nematoda, having an elongated, cylindrical body; a roundworm
Nitrification	The biological oxidation of ammonia with oxygen, then into ammonium, then into nitrite followed by the oxidation of these nitrites into nitrates
Oligosaccharides	A saccharide polymer containing a small number (typically two to ten) of simple sugars (monosaccharides)
pH	The symbol for the logarithm of the reciprocal of hydrogen ion concentration in gram atoms per liter, used to express the acidity or alkalinity of a solution on a scale of 0 to 14, where less than 7 represents acidity, 7 neutrality, and more than 7 alkalinity
Phenotype	The physical appearance or biochemical characteristic of an organism as a result of the interaction of its genotype and the environment
Photoperiod	The physiological reaction of organisms to the length of day or night. It can also be defined as the developmental responses of plants to the relative lengths of the light and dark periods

Photoperiod	The developmental responses of plants to the relative lengths of the light and dark periods
Photosensitivity	The amount to which an object reacts upon receiving photons, especially visible light
Polyphyletic origin	Developed from more than one ancestral group of plants or animals.
Polysaccharides	Long carbohydrate molecules of monosaccharide units joined together by glycosidic bonds. They range in structure from linear to highly branched
Primary tillage	Tillage that is deeper and more thorough. It tends to produce a rough surface finish
Pyrolysis oil	Also known as bio-oil is a kind of tar (a mixture of hydrocarbons and free carbon) and normally contains too high levels of oxygen to be a hydrocarbon
Reducing sugar	A sugar that serves as a reducing agent due to its free aldehyde or ketone functional groups in its molecular structure. Examples are glucose, fructose, glyceraldehydes, lactose, arabinose and maltose.
Saline soils	Non-sodic soil containing sufficient soluble salt to adversely affect the growth of most crop plants with a lower limit of electrical conductivity of the saturated extract (ECe) being 4 deciSiemens / meter (dS/m)
Secondary tillage	Tillage that is shallower and sometimes more selective of location. It tends to produce a smoother surface finish
Sorbitol	Also known as glucitol, is a sugar substitute, which the human body metabolises slowly. It can be obtained by reduction of glucose
Sori	Plural of sorus. A cluster of sporangia (structures producing and containing spores) in ferns and fungi
Sugar refractometer	Device used to measure the specific gravity before fermentation to determine the amount of fermentable sugars which will potentially be converted to alcohol.
Swathing	Process of cutting grain crops and forming windrows
Taxa	(Singular: taxon) is a group of one (or more) populations of organism(s), which a taxonomist adjudges to be a unit
Tillage	The agricultural preparation of soil by mechanical agitation of various types, such as digging, stirring, and overturning

Tilth	A descriptor of soil. It combines the properties of particle size, moisture content, degree of aeration, rate of water infiltration, and drainage into abbreviated terms in order to more easily present the agricultural prospects of a piece of land
Trait	(genetics) Characteristics or attributes of an organism that are expressed by genes and/or influenced by the environment
Waterlogging	The saturation of soil with water
Windrows	A row of cut (mowed) small grain crop. It is allowed to dry before being baled, combined, or rolled

Abbreviations

%	: Percent
°C	: Degree centigrade
°N	: Degrees north
°S	: Degrees south
1st	: First
2nd	: Second
AB	: Acetogenic bacteria
AD	: Anno Domini (After Christ)
AD	: Anaerobic digestion
Al	: Aluminium
AM	: Acetotrophic methanogens
BC	: Before Christ
BNI	: Biological Nitrification Inhibition'
CHP	: Combined Heat and Power
cm	: Centimetre
CH_4	: Methane
CO_2	: Carbon dioxide
CO	: Carbon monoxide
Cu	: Copper
dS	: DeciSiemens
e.g.	: For example
FB	: Fermentative bacteria
Fe	: Iron
g	: Gram
GHG	: Greenhouse gases
GJ	: Gigajoule
h	: Hour
H	: Hour
H_2	: Hydrogen
H_2O_2	: Hydrogen peroxide
H_2S	: Hydrogen sulfide
ha	: Hectares
HM	: Hydrogenotrophic methanogens
J	: Joule
K_2O	: Potassium oxide
kg	: Kilogram
kJ	: Kilojoule
kWel	: Kilowatt Electric
l	: Litre
m	: Meter
m^2	: Square meter
m^3	: Cubic meter
Mg	: Megagram
MJ	: Megajoule
ml	: Millilitre
mm	: Millimeter
Mn	: Manganese
N	: Nitrogen
NaCl	: Sodium Chloride
NaOH	: Sodium hydroxide
$NaSO_4$	: Sodium Sulfate
NH_3	: Ammonia
P	: Phosphorous
P_2O_5	: Phosphorous pentoxide
RUE	: Radiation use efficiency
t	: Tonnes
USA	: United States of America
v	: Volume
WUE	: Water use efficiency
Zn	: Zinc

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