Chapter 3

Bioethanol production

Biofuel production based on vegetable feedstock can be made through different technology routes — similarly to alcoholic beverages —, subject to dissimilar advantages and limitations, as shown in Table 6. Bioethanol is clearly at a more advanced development stage than biodiesel and it has been more effectively included in the energy matrix of several countries. In 2006 bioethanol represented an energy supply of around 3% of the world gasoline demand, that is, ten times the concomitant biodiesel production [EIA 2008].

This chapter reviews issues of biofuels production from different biomass sources. The chapter starts with a discussion of the main feedstocks and production technologies (Section 3.1), followed by a broad view of the agricultural and industrial stages of production in each case, addressing significant circumstances and current and prospective productivity indicators. In this regard, sugarcane (Section 3.2) and corn bioethanol (Section 3.3) production systems will be analyzed in detail, as they account for the major share of global biofuels production. The chapter also discusses, but to a lesser extent, bioethanol production systems of other feedstock, such as cassava, wheat, beet and sorghum (Section 3.4). The chapter closes with a review of productivity, emission and energy balance issues (Section 3.5), which focuses on recommendations about criteria to considered when choosing feedstock for bioethanol production; the analysis stresses the overall performance of different biomass sources for solar energy conversion into biofuels and the consequent emission of GHG per unit of existing energy. Values for these parameters are presented at the end of this chapter both for sugarcane and corn bioethanol.

3.1 Bioethanol production feedstock and technologies

Table 6, displays liquid biofuels configurations for bioethanol and biodiesel. Through biological routes, bioethanol may be produced based on any biomass containing significant amounts of starch or sugars. Nowadays, there is a slight predominance of production based on starchy materials (53% out of the total), such as corn, wheat and other cereals and grains. In such cases, conversion technology typically starts by separating, cleaning and milling the grains. Milling may be wet, where grains are steeped and fractionated before the starch conversion into sugar (wet milling process), or dry, when this is done during the conversion process (dry milling process). In both cases starch is typically converted into sugars by means of an enzymatic process, applying high temperatures. Sugars released are then yeast-fermented and the wine produced is distillate to purify bioethanol. In addition to bioethanol, these processes typically involve several co-products, which differ according to the biomass used. In Table 6, only the currently commercially implemented routes were included; other alternatives under development, such as the ones involving hydrolysis of cellulosic materials will be addressed in Chapter 5.

Table 6 **– General biofuels outlook**

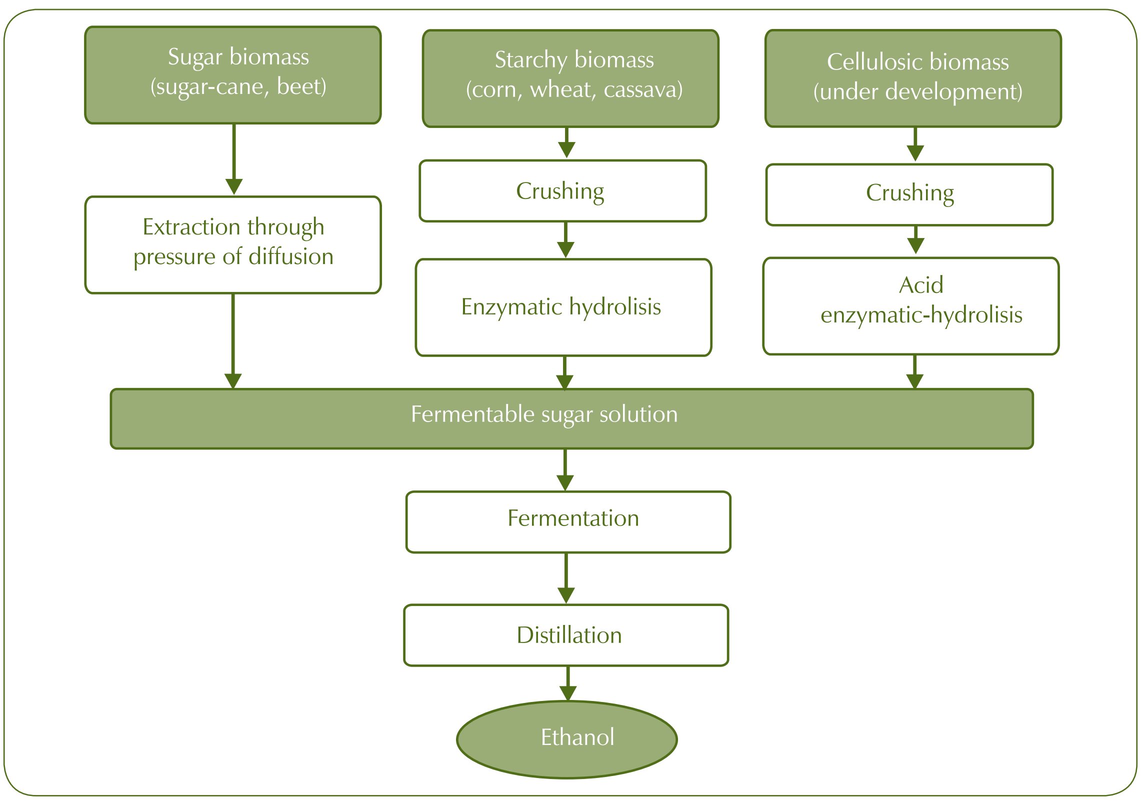
Biofuel	Feedstock	Reduction of GHG emissions	Production Cost	Biofuel production per hectare	Soil
Bioethanol	Grains (wheat, corn)	Moderate to low	Moderate	Moderate	Fertile soils
Bioethanol	Sugarcane	High	Low	High	Fertile soils
Biodiesel	Seed oils (rapeseed, soybean etc.)	Moderate	Moderate	Low	Fertile soils
Biodiesel	Palm oil	Moderate	Moderate to low	Moderate	Wet and coastal soils

Source: Adapted from IEA (2005).

Sugar-based bioethanol production — such as sugarcane and sugar beet — is a simple process and requires one step less than starch-bioethanol, since sugars are already present in biomass. Generally, the process is based on extraction of sugars (by means of milling or diffusion), which may be then taken straight to fermentation. The wine is distilled after fermentation, such as in starch-based production. Figure 7 summarizes the technology routes for bioethanol production, considering different feedstocks. It should be noted that cellulose-based bioethanol production still is in laboratory and pilot-plant stages, with technological and economic obstacles to overcome and not having yet significant presence within the energy context.

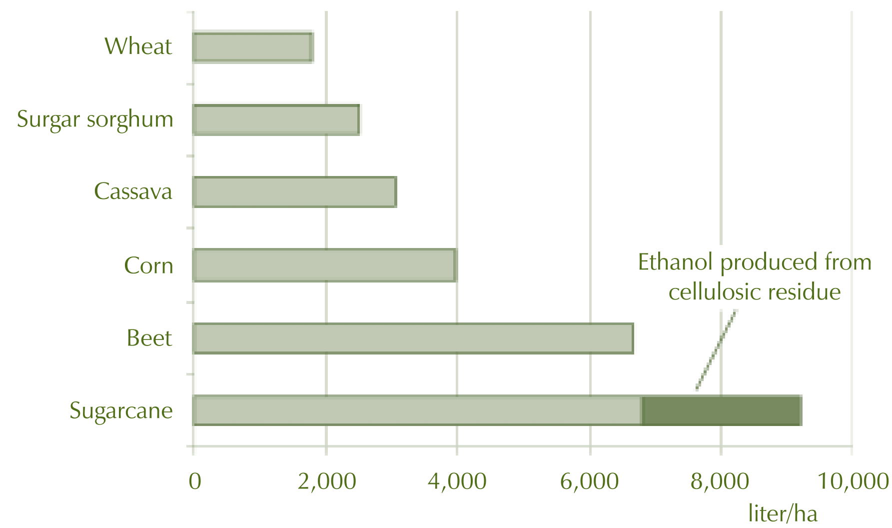
Graph 8 compares different routes for bioethanol production, illustrating the differences within productivity indexes per cultivated area. Data is from the literature [GPC (2008)] and in the cases of sugarcane and sorghum it has been modified to fit the analyses presented in this study. The results correspond to crops with good productivity, which, in some cases can imply high inputs use. Industrial technologies for sugar and starch conversion into bioethanol, underlying such graph, may be considered as well-developed and available, except those related to hydrolysis of lignocellulosic materials, currently under development (see Chapter 5). The Graph takes into account an 80-ton production of sugarcane per hectare, a productivity of 85 litres of bioethanol per ton of processed sugarcane and the use of 30% of bagasse available and half of the straw converted into bioethanol at a ratio of 400 litres per ton of dry cellulosic biomass.

***Figure 7* – Technological routes for ethanol production**



Source: Elaborated by Luiz Augusto Horta Nogueira.

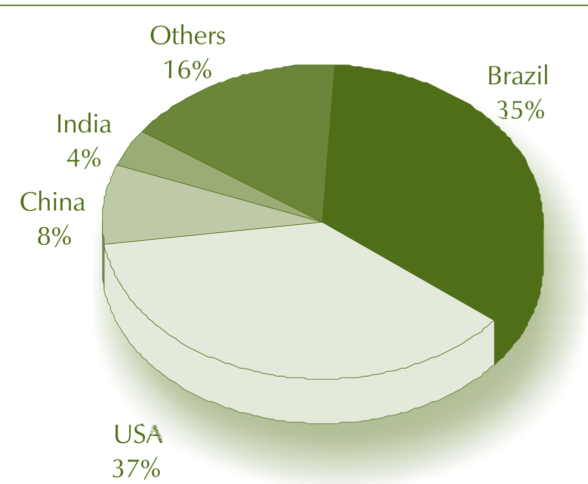
Graph 8 **– Average ethanol productivity per area for different crops**



Source: Adapted from GPC (2008).

Out of the 51 billion litres of bioethanol produced in 2006 [F. O. Licht (2006)], 72% was produced by US (corn bioethanol) and Brazil (sugarcane bioethanol), as shown in Graph 9 [RFA (2008)]. Because of their significant importance to the biofuel context, production technologies involving corn and sugarcane will be discussed at large in the following sections, addressing the most relevant agricultural aspects.

Graph 9 **– Distribution of world ethanol production in 2006**



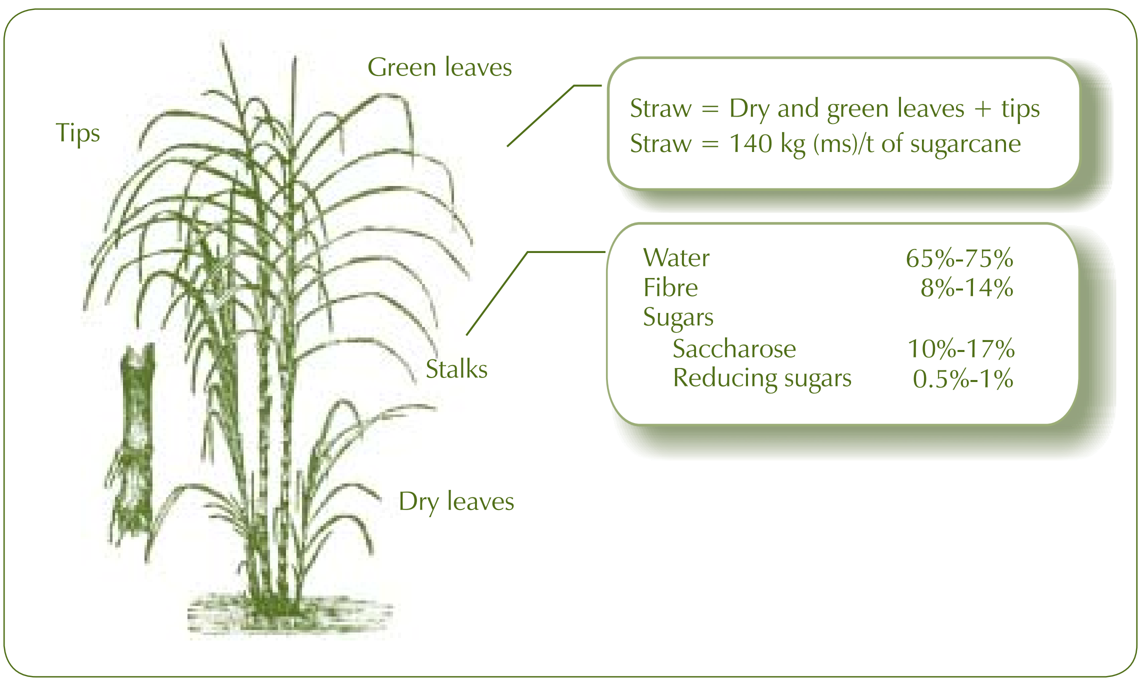
Source: Produced based on RFA (2008).

3.2 Sugarcane bioethanol

Sugarcane is a semi-perennial plant with C4-type photosynthetic cycle, genus *Saccharum*, family Gramineae, consisting of perennial tall grass species, native of warm and tropical Asian temperature zones, especially from India. The aerial part of the plant is essentially formed by *stalks*, containing saccharose, and by *tips* and *leaves*, which form the sugarcane straw, as shown in Figure 8. These components altogether sum around 35 tons of dry material per hectare.

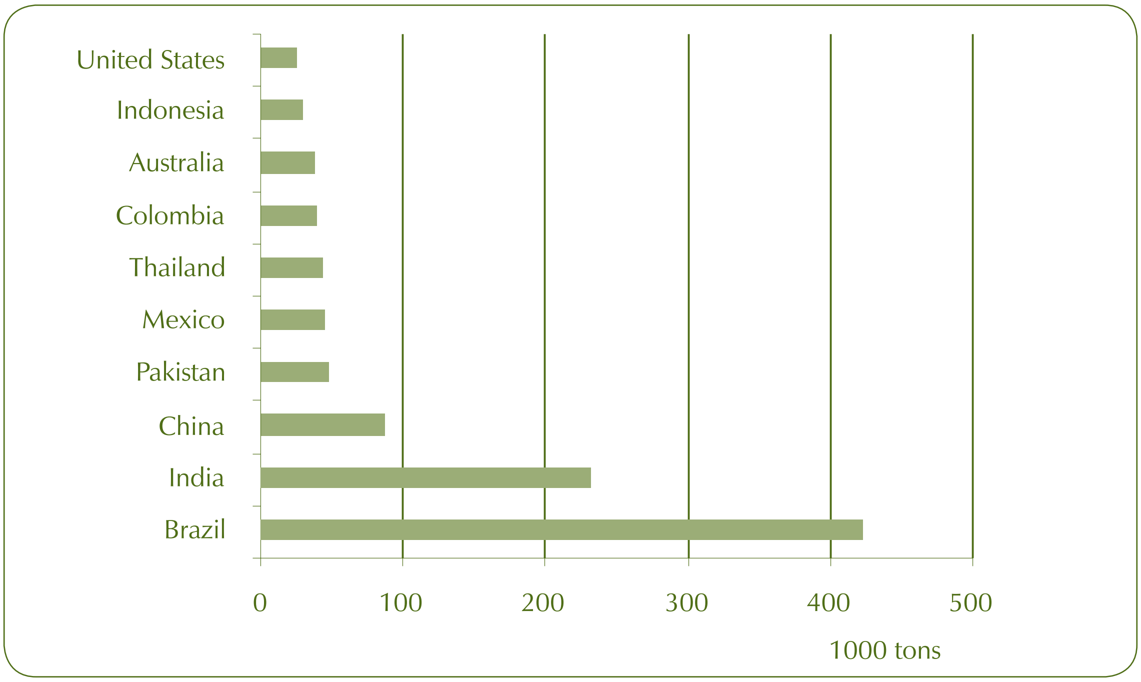
Sugarcane is the one of the most important commercial crops all over the world. It occupies more than 20 million hectares in which nearly 1,300 million tons were produced in 2006/2007. Brazil stands out as the leading producer with a cropland area of around 7 million hectares, representing close to 42% of total production. The internationally adopted sugar harvest season begins in September and ends in August of the following year. Graph 10 presents the ten leading sugarcane producers of 2005 crop [FAOSTAT (2008a)].

Figure 8 **– Typical sugarcane biomass structure**



Source: Seabra (2008).

Graph 10 – **Leading sugarcane producing countries in 2005**



Source: FAO (2007).

The ideal weather to cultivate sugarcane is one that has two distinct growing seasons: a warm and wet season, to make possible the sprouting, tilling and vegetative development, followed by a cold and dry season, which promotes the maturation and the consequent accumulation of saccharose in stems. Sugarcane does not attain good productivity in climates such as those found in wet equatorial regions; thus, it makes little sense for the Amazon forest to be used for extensive commercial sugarcane cultivation.

The complete sugarcane cycle varies, depending on the local weather, crop varieties and practices. In Brazil the cycle typically requires six years and comprises five cuts, as described below. The first cut is generally made 12 or 18 months after planting (depending on sugarcane varieties), when the so-called "cane-plant" is harvested. The other cuts, from ratoon cane (cane stalks resprouting), are harvested once a year four years in a row, with a gradual reduction of productivity. At this moment it is generally more cost-effective to reform (replant) the sugarcane plantation. The old sugarcane is then replaced by a new crop and a new production cycle begins. During sugarcane crop reform the cropland remains in fallow for some months and may receive other short-cycle crops, such as leguminous plants.

Following the sugarcane six-years production cycle, production areas must be subdivided into large planting fields at different cycle stages, with around one sixth of the total area for each stage to obtain a fairly stable production for several harvests and make appropriate use of resources and good agricultural practices (machinery and manpower). A significant consequence of this production cycle in sugarcane bioethanol production units is that agricultural activities must start two to three years before the effective industrial production, to allow for a fairly stable feedstock production within three to four years. Techniques such as direct seed cropping schemes and controlled traffic farming systems are being developed to reduce costs and preserve soil fertility. Such techniques allow increasing the number of cuts while maintaining high productivity levels [CGEE (2007b)].

Given that the typical sugarcane production cycle has five cuts during six years, average annual productivity must take into account the sugarcane crop reform period. Moreover, as part of the sugarcane produced (around 8%) is used to reform (replant) the sugarcane field, annual productivity measured in tons of sugarcane effectively processed per hectare of cropland is below the total productivity computed on the basis of sugarcane harvested.

On average, annual productivity is highly influenced by climatic variability and by specificities of producing areas, with ranges from 50 t/ha to 100 t/ha (weight of wet stem). Average productivity in Brazil is around 70 t/ha of sugarcane, which is equivalent to the figures from the best producing regions in other countries. Although there are sugarcane productivity records reaching 200 t/ha [Janick (2007)], in the Center-South Region of Brazil — where most of Brazilian mills are located — these rates range from 78 t/ha to 80 t/ha. In the State of São Paulo — the main producer — they range from 80 t/ha to 85 t/ha. [Unica (2008)]. Annex 2 presents sugarcane average productivity values in Brazil, in tons per hectare harvested.

Table 7 presents an overview of the main sugarcane crop parameters, as practiced in the Brazilian Center-South Region [Macedo (2005) and CTC (2005)]. Pol and fibre percentage based on mass of sugarcane correspond, respectively, to the saccharose apparent content and the bagasse content in sugarcane. In addition to saccharose, depending on its maturation, sugarcane contains around 0.5% of other sugars (such as glucose and fructose) not used for production of solid sugar, but possible to be used to produce bioethanol [Fernandes (2003)].

Table 7 also shows that fertilizers demand for sugarcane crops is reduced when compared to other crops, because sugarcane industrial waste returns to the cropland as fertilizer. The use of synthetic nitrogen is low, and in the areas where vinasse is applied all potassium is supplied by fertigation. In spite of being a crop with high water demand, rainfall rates higher than 800 mm (best scenario between 1,200 mm and 1,500 mm) and properly distributed (well-defined rainy and drain periods) are enough to reach good productivity. In the Brazilian Center-South typical producing units (using half of sugarcane to produce sugar and the other half to produce bioethanol) the application of vinasse represents around 15 mm to 20 mm in 30% of the sugarcane cropland area and virtually eliminates the need for irrigation. The values shown for vinasse and cake filter application refer to values recommended in typical conditions for the State of São Paulo, according to the environmental laws.

Table 7 – **Main sugarcane agricultural parameters in the Brazilian Center-South**

Indicator	Percentage
Productivity	87.1 tc/ha
Harvest of green sugarcane (without burning)	30.8%
Mechanized harvest	49.5%
% sugarcane pol (content of saccharose)	14.22
% sugarcane fibber (content of bagasse)	12.73
Fertilizers	
P_2O_5	
Cane-plant	120 kg/ha
Ratoon cane without vinasse	25 kg/ha
K_2O	
Cane-plant	120 kg/ha
Ratoon cane without vinasse	115 kg/ha
Nitrogen	
Cane-plant	50 kg/ha
Ratoon cane with vinasse	75 kg/ha
Ratoon cane without vinasse	90 kg/ha
Limestone	1.9 t/ha (only in planting)
Herbicide	2.20 kg/ha (recommended value)
Insecticide	0.12 kg/ha (recommended value)
Other agrochemicals	0.04 kg/ha
Application of filter cake	5 t (dry milling process)/ha
Application of vinasse	140 m^3/ha

Source: Macedo (2005a) and CTC (2005).

(a) (b)

Sugarcane harvest: (a) manual with burning and (b) mechanized without burning.

Sugarcane harvest periods vary according to rainfall to allow cutting and transportation operations while reaching the best maturation point and maximizing sugar accumulation. In the Brazilian Center-South Region harvest goes from April to December, while in the Northeast Region harvest takes place from August to April. The traditional harvest system — which is still used in nearly 70% of sugarcane crops in Brazil and involves the previous burning of the sugarcane crop and the manual cut of the whole stalk sugarcane — is being progressively replaced by the mechanized harvest of green chopped sugarcane (without burning), due to environmental restrictions on burning practices. Recent agreements between the government and producers made for an estimate of all sugarcane to be mechanically harvested by 2020, without previously burning the sugarcane crop.

After it is cut sugarcane is promptly transported to the mill to avoid saccharose losses. Except for a few companies that use some sort of waterway transport, the transportation system is based on trucks — single-trailer truck, twin-trailer truck, triple trailer truck, road train — with cargo capacity between 15 and 60 tons. In recent years sugarcane logistics has undergone significant development, involving integrated operations of cutting, shipment and transportation, to cut costs and diminish soil compaction.

Figure 9 **– Distribution of the 350 sugarcane processing mills in Brazil**

Source: CGEE (2006).

Sugarcane cannot be stored for more than a few days and mills operate only during the harvest period, irrespective of the type of facility. The initial processing stages for bioethanol are basically the same as for sugar production, as shown in Figure 10. Once in the mill sugarcane is generally washed (only the whole stalk sugarcane) and sent to the preparation and extraction phases. Extraction is made by roll-mills — arranged in sets from four to seven successive three-roll mills — that separate the sugarcane juice containing saccharose from the bagasse, which is sent to the mill's power plant to be used as fuel. In some new units implemented in Brazil extraction by diffusion is being adopted and expected to deliver some advantages as far as energy is concerned. In that process chopped and shredded sugarcane is repeatedly washed with hot water inside diffusers, where it releases sugars through a leaching process. Then the product is pressed through a drying roller, which generates the bagasse to be used in boilers. Produced in the mill or diffuser, the juice containing sugars can be then used in sugar or bioethanol production.

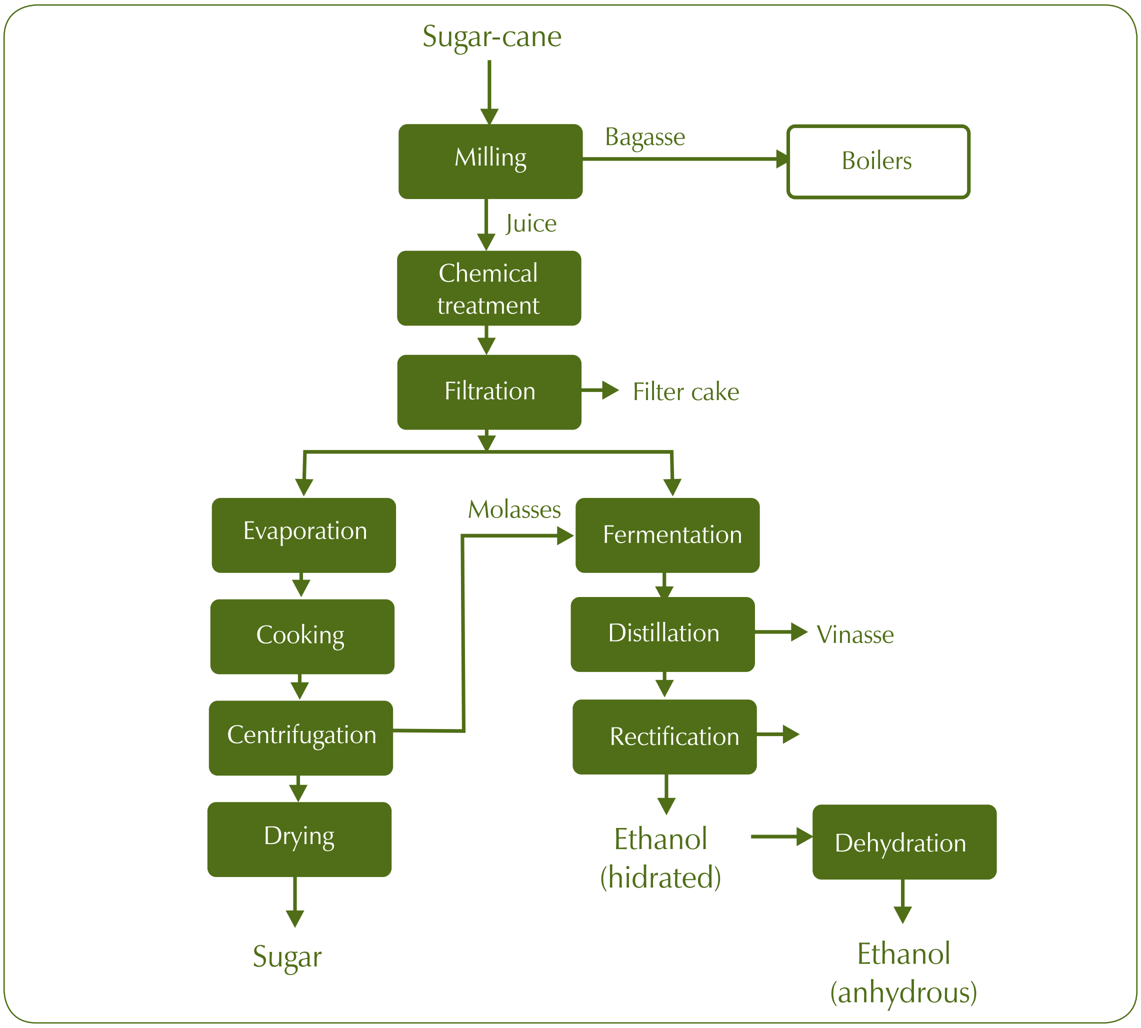
Sugarcane transport by triple trailer truck in Brazil.

In sugar production the juice is initially screened and chemically treated for coagulation, flocculation and precipitation of impurities, which are eliminated through decanting. The filter cake, used as fertilizer, is generated by recovering sugar out of the decanted slurry by means of rotary vacuum filters. The treated juice is then concentrated in multiple-effect evaporators and crystallized. In such process only part of the saccharose available in the sugarcane is crystallized and the residual solution with high sugar content (honey) can be used in the process once again to recover more sugar. The honey produced — also called molasses — does not return to the sugar manufacturing process but can be used as an input for bioethanol production through fermentation, because it still contains some saccharose and a high amount of reducing sugars (such as glucose and fructose, resulting from saccharose decomposition).

Thus, sugarcane bioethanol production may be based on fermentation, whether using the sugarcane juice alone or using a mix of juice and molasse, the latter being more frequently practiced in Brazil. In sugarcane-juice bioethanol the first stages of the manufacturing process, from sugarcane receipt to initial juice treatment, are similar to the sugar manufacturing process. In a more well-rounded treatment the juice is limed, heated and decanted as in the sugar process. After treatment the juice is evaporated to balance its sugars concentration and, in some cases, it is mixed to molasse, generating sugarcane mash, a sugary solution which is ready to be fermented.

The mash is sent to fermentation reactors, where yeasts are added to it (single-celled fungi of *Saccharomyces cerevisae* species) and fermented for a period ranging from 8 to 12 hours, generating wine (fermented mash, with ethanol concentration from 7% to 10%). The most common fermentation process in Brazilian distillery is Melle-Boinot, characterized by the recovery of wine yeasts by means of centrifugation. Then, after fermentation yeasts are recovered and treated for new use, while the wine is sent to distillation columns.

Figure 10 **– Sugar and sugarcane-based bioethanol production flowchart**



Source: Seabra (2008).

In distillation bioethanol is initially recovered in hydrated form. Nearly 96° GL (percent in volume) corresponds to around 6% of water in weight, producing vinasse or stillage as residue, generally at a ratio of 10 to 13 litres per litre of hydrated bioethanol produced. In this process, other liquid fractions are also separated, producing second generation alcohols and fusel oil. Hydrated bioethanol can be stored as final product or may be sent to the dehydration column. Nevertheless, as it is an azeotropic mixture, its components cannot be separated by distillation only. The most commonly-used technology in Brazil is dehydration with addition of cyclohexane, forming a ternary azeotropic mixture, with boiling point lower than that of anhydrous bioethanol. In the dehydration column, cyclohexane is added on top, and the anhydrous bioethanol is removed from the bottom, with nearly 99.7° GL or 0.4% of water in weight. The ternary mixture removed from the top is condensed and decanted, while the part with high water content is sent to the cyclohexane recovery column.

Sugarcane processing mill in Brazil.

Bioethanol dehydration also can be made by adsorption with molecular sieves or by means of extractive distillation with monoethyleneglycol (MEG), which stand out as providers of lower energy consumption, as well as by their higher costs. Due to increasing requirements in foreign markets several bioethanol producers in Brazil and in other countries have been choosing molecular sieves, since they allow producing anhydrous bioethanol free from contaminants.

The possibility of using sugars from sugarcane exclusively or non-exclusively to produce bioethanol represents a significant adaptation technology in this agroindustry, which sugar mills can use to arbitrage — within certain limits — a cost-effective production program, depending on price conditions, existing demand and other market perspectives. Actually, to take advantage of such flexibility several Brazilian mills have sugar and bioethanol manufacturing lines, each one capable of processing 75% of the juice produced, allowing a margin of 50% of the total processing capacity against the extraction capacity of the mill.

Water discharges in bioethanol production are relatively high. Currently, considering the Brazilian Center-South scenario, around 1.8 m^3 of water are collected per ton of processed sugarcane; however, such figure is significantly going down as a result of recycling initiatives, which allow reducing both the water collection level and treated water disposal. This aspect will be analyzed in-depth in Chapter 6.

Considering the entire sugarcane bioethanol production cycle, the residues generated in the process are vinasse (from 800 to 1,000 litres per ton of processed sugarcane for bioethanol), filter cake (around 40 kg of wet output per ton of processed sugarcane) and boiler ashes [Elia Neto (2007)]. As said before, in the Brazilian mills such residues are well appreciated by-products that once recycled can be used as fertilizers, contributing to both significantly reduce the need for mineral fertilizers and avoid the need for irrigating sugarcane crops.

As bioethanol production involves significant water elimination, the energy demand is high, particularly concerning thermal power, as shown in Table 8. Steam demand in hydrated bioethanol considers the conventional technology consuming 3.0 kg to 3.5 kg of steam per litre of bioethanol produced; in anhydrous ethanol demand is estimated considering an azeotropic distillation process using cyclohexane that consumes 1.5 kg to 2.0 kg of steam per litre of bioethanol produced. As far as electric power demand is concerned, there are slight distinctions between processes, but all of them are around 12 kWh per ton of processed sugarcane.

Table 8 **– Energy demand in sugarcane processing**

Energy	Unit	Sugar	Hydrated bioethanol	Anhydrous bioethanol
Thermal Steam saturated at 1.5 bar (manometric method), for heaters, evaporators and distillation	kg/tc	470-500	370-410	500-580
Mechanical Driving of sugarcane preparation and milling systems and motopumps	kWh/tc	16	16	16
Electric Various electric engines, lighting and other charges	kWh/tc	12	12	12

Source: Pizaia (1998).

In the sugarcane-based bioethanol agroindustry all energy consumed in the process can be supplied by a heat-and-power production system (cogeneration system) installed in the mill, using only bagasse as an energy source. Actually, many sugarcane mills all over the world produce a significant part of the energy they consume. Particularly in Brazil, mills are energy self-sustained and they often manage to export increasing amounts of electric power surpluses to the public grid, thanks to the growing use of energy-efficient equipment. More details on the arrangement of power facilities in mills and their energy-production potential is discussed in Chapter 4.

Regarding industrial yield, one ton of sugarcane used exclusively for sugar production generates around 100 kg of sugar as well as over 20 litres of bioethanol using molasses. Data for Brazil is presented in Table 9, using average figures from nearly 60 mills in the State of São Paulo (figures adapted from CTC, 2005); losses refers to an average sugarcane with a 14% saccharose content. One ton of sugarcane may produce 86 litres of hydrated bioethanol in bioethanol-only production; or 100 kg of sugar plus 23 litres of hydrated bioethanol out of molasses in sugar production. Figures in the last case correspond to a sugar production process with two masses (successive crystallization processes), in which honey is not depleted but sent with relative high content of saccharose for bioethanol production, which allows enhancing the product quality and reducing energy consumption to produce sugar. In a nutshell, synergies and complementary relationships between the sugar and bioethanol production help cutting costs and increasing the efficiency of agroindustrial processes.

Table 9 **– Average losses and yields of sugarcane mills**

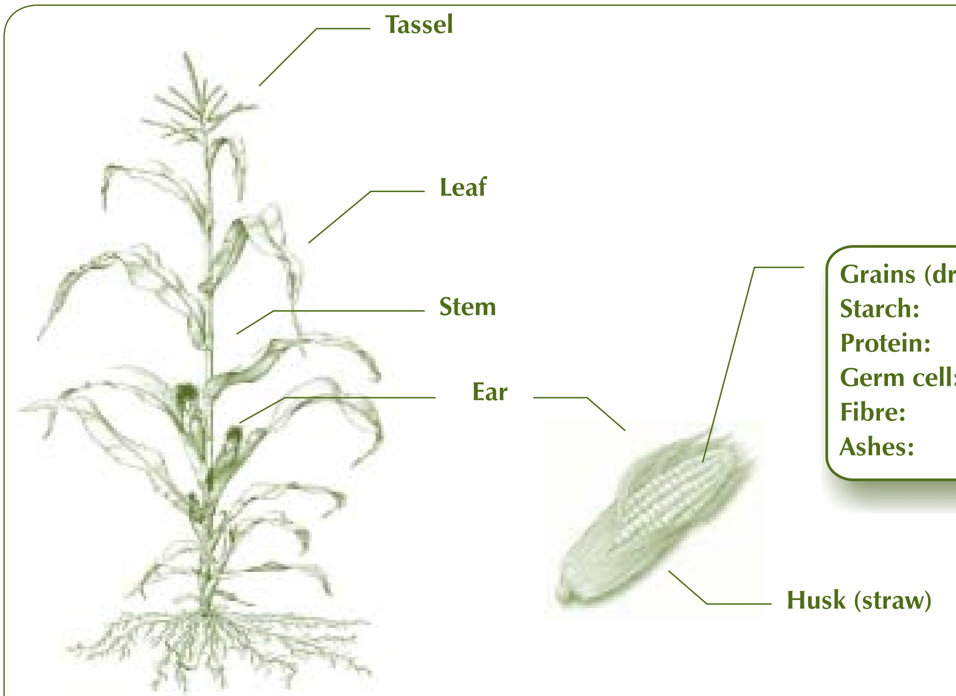
Item	Sugar or yield loss
Sugarcane washing	0.7%
Extraction	3.9%
Filter cake	0.5%
Not defined	3.5%
Distillation	0.2%
Fermentation yield	90.0%
Overall yield	
Sugar	100 kg/t cane (+ 23 litres/t cane)
Hydrated bioethanol	86 litres/t cane

Source: Figures adapted from CTC (2005).

3.3 Corn bioethanol

Similarly to sugarcane, corn (*Zea mays spp.*) is a C4 plant from the grass family, with annual production cycle. Originated in Mesoamerica, corn is currently cultivated in all continents and occupies nearly 147 million hectares, producing around 725 million tons in 2004 [Faostat (2008a)]. It is an important food item in several countries, as human and animal food.

Figure 11 – **Typical structure of corn biomass**



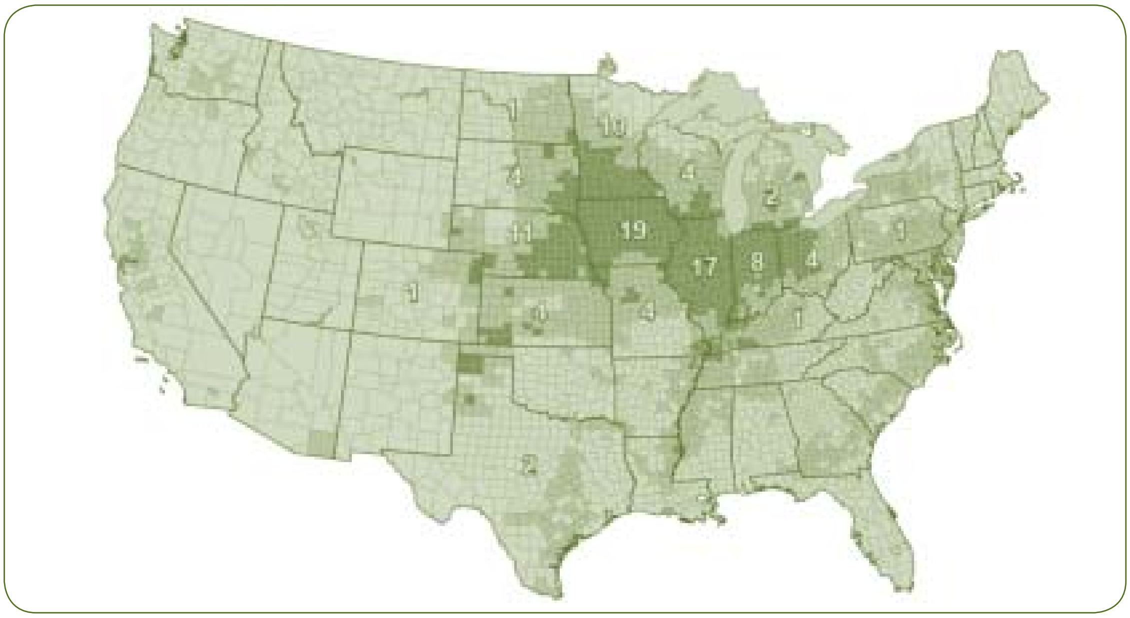
Grains (dry matter):	
Starch:	**70%-75%**
Protein:	**10%**
Germ cell:	**4%-5%**
Fibre:	**3%-4%**
Ashes:	**2%**

Source: Seabra (2008).

The United States is the leading world's corn producer, responsible for nearly half of the total global production. In 2006 US corn production was over 267 million tons of grains from a cropland area of over 28 million hectares [USDA (2008)]. Out of that total, more than 50% was used in animal feeding, while less than 20% went to the bioethanol industry [Iowa Corn (2008)]. Most production comes from the so-called Corn Belt region, especially the States of Iowa and Illinois, where it is the main crop, as shown in Figure 12. Corn is also the main feedstock in US bioethanol production: more than 98% of bioethanol produced in the US is from corn.

In temperate zones corn is planted in the Spring (April and May in the Northern Hemisphere) because it is a plant that cannot endure cold weather. Corn crops typically involve a crop rotation with some sort of nitrogen-fixing plant, generally alfalfa or soybean (in long-summer regions), and occasionally a third crop may be used, such as wheat. In the traditional model soil is ploughed every year, but minimum tillage is becoming increasingly common. In the US the harvest season goes from September through November and it generally performed by a harvesting machine. In mechanical harvesting the ear is separated from the stem and the kernels are extracted from the ear; the straw and corncob are left on the field.

Figure 12 **– Distribution of corn production in the United States***



Source: Seabra (2008).
* Map numbers indicate percent contribution of each State.

Corn harvest.

US average productivity is around 9 tons of kernels per hectare [USDA (2008)]. Actually, kernels account for around 50% of plant dry matter, which also includes the stem, leaves, straw and corncob [Pordesimo et al. (2004)], amounting to 15 tons of dry matter per hectare.

Although this biomass is expected to be used as an energy alternative, it is important that most of it remains on the field after harvest to preserve soil fertility [Blanco-Canqui and Lal (2007)].

As compared with sugarcane, corn demands a relatively larger amount of fertilizers, as shown in Table 10. Results are weighted for irrigated and non-irrigated areas [Pimentel and Patzek (2005)]. When it comes to water consumption, total demand is around 5.6 thousand m^3 per hectare, although less than 10% of the cropland in the United States needs irrigation [NGCA (2008)].

Table 10 **– Fertilizers and agrochemicals demands for corn production in the USA**

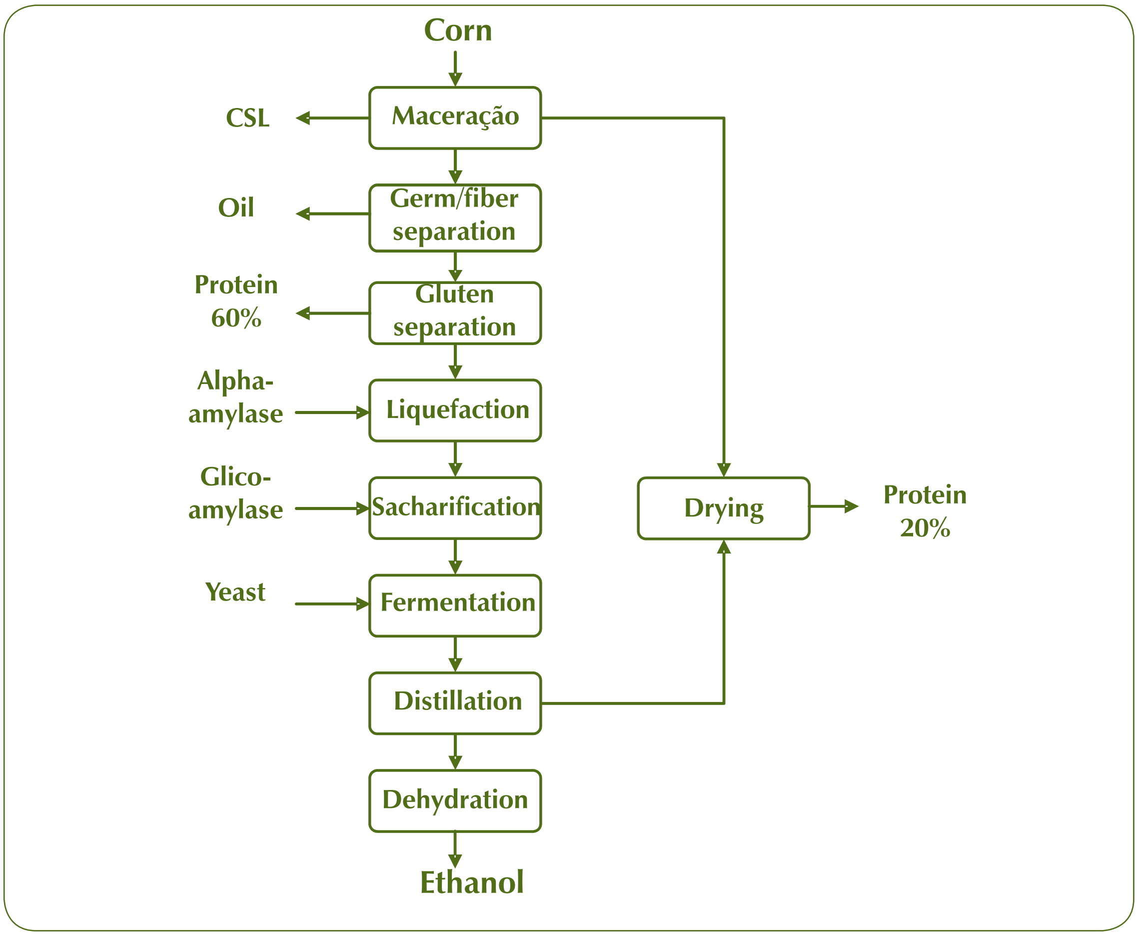
Inputs	Demand
Nitrogen	153 kg/ha
Phosphorus	65 kg/ha
Potassium	77 kg/ha
Limestone	1,120 kg/ha
Seeds	21 kg/ha
Irrigation (in 10% of cropland)	8.1 cm/ha
Herbicide	6.2 kg/ha
Insecticide	2.8 kg/ha

Source: Pimentel and Patzek (2005).

Bioethanol may be produced using corn by means of wet or dry milling. Wet milling was the most common option until the 1990s, although nowadays dry milling has become the preferred process. Wet milling provides a large variety of products; however, improvements have made dry-milling processing the best option considering its lower investment and operation costs that enable substantial cuts in bioethanol final cost [Novozymes (2002)].

In wet processing (Figure 13) the corn kernel portions are separated and several products, such as proteins, nutrients, carbon dioxide (CO_2, used in soft drink plants), starch, and corn oil are recovered. While corn oil is the golden product, starch (and consequently bioethanol) is the one produced in larger amounts yielding about 440 litres of bioethanol per dry ton of corn, as shown in Table 11.

Figure 13 – **Flowchart of wet-milling corn-based bioethanol production**



Source: Wyman (1996).

In dry milling (Figure 14) the only bioethanol co-product is a protein supplement for animal feeding called DDGS (Distillers Dried Grains with Solubles). In this process ground corn kernels are blended with water and enzymes (alpha-amylase) to hydrolyse the starch into smaller sugar chains. In the next stage the chains are saccharified by glucoamylase and the solution produced is then fermented. In some units, during these liquefaction/saccharification operations, a part of fine vinasse is recycled (backsetting process) to reduce the pH and provide nutrients for fermentation.

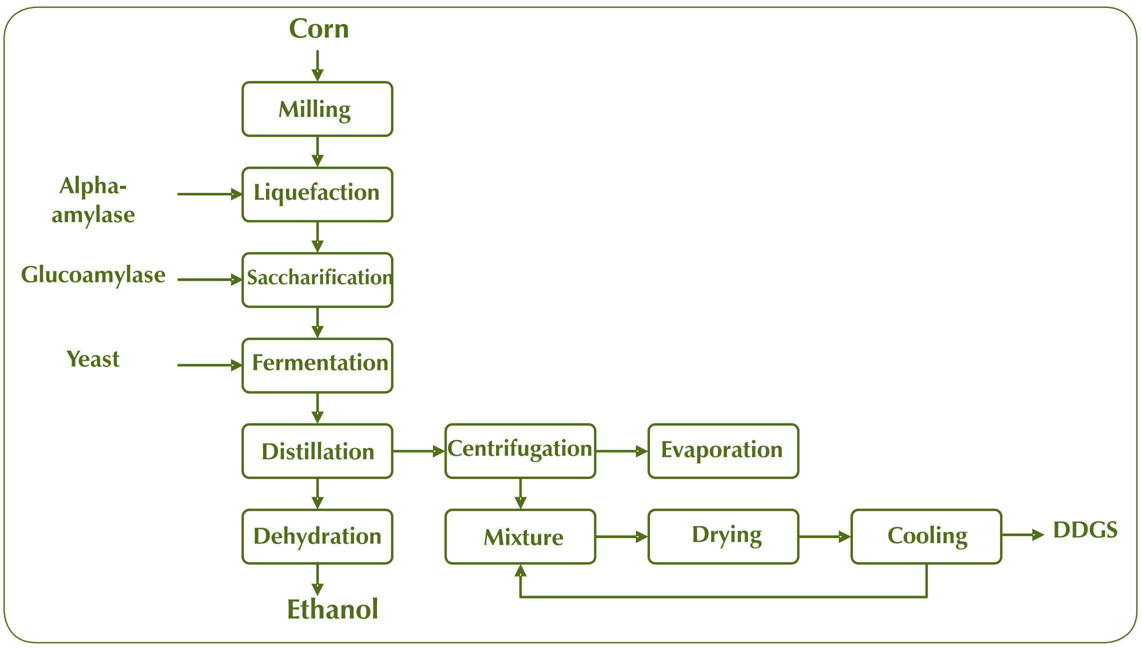
The sugar release process, although rapid in the initial stages, quickly slows down, which may require remaining 48 to 72 hours in the reactors to get maximum starch saccharification. In order to reduce such time and contamination risks, several units develop saccharification and fermentation simultaneously. In this case, the conversion to glucose is also reduced. However, in processes using backsetting recycling permits to re-use sugars not converted initially.

Table 11 **– Yield of co-products in wet milling**

Product	Yield
Corn oil	34–38 kg/t corn
Protein 20%	306 kg/t corn
Protein 60%	68 kg/t corn
CO_2	308 kg/t corn
Bioethanol	440 litres/t corn

Source: Wyman (1996).

Figure 14 **– Flowchart of dry-milling corn-based bioethanol production**



Source: Wyman (1996).

As in the case of sugarcane bioethanol, in the fermentation phase glucose is transformed into bioethanol by the action of *Saccharomyces cerevisiae* yeast, and the wine produced is then sent to distillation. Vinasse produced in this stage is sent to a set of centrifuges where fine vinasse is separated. The remaining vinasse is usually concentrated in evaporators, producing syrup with approximately 50% of humidity. The syrup is combined with solid elements removed from the centrifuge and nearly 10% of humidity to obtain DDGS. Other distillation stages are equivalent to the sugarcane bioethanol process used in Brazil. The only difference is that in the US dehydration with molecular sieve is already the most used process to produce anhydrous bioethanol. As for yields, typically around 460 litres of anhydrous bioethanol and 380 kg of DDGS are obtained per dry ton of corn [Wyman (1996)].

Corn bioethanol production mill in the USA.

3.4 Biothanol based on other feedstocks

As mentioned already, any feedstock with enough content of sugar or starch may be converted into bioethanol. Therefore, in addition to sugarcane and corn, some countries have considered other starchy of sugary crops, such as cassava, wheat, sugar beets and sweet sorghum. These alternatives are briefly addressed below.

Cassava (*Manihot esculenta*) is native to Brazil and largely grown in tropical regions of Africa and Asia. In addition to its broad use as basic food in human and animal diet, in Thailand and China cassava is semi-processed for export (as *tapioca*) and used locally to produce bioethanol for beverages. The main advantage of cassava is the high content of starch in its roots, ranging from 20% to 30%; in addition, it is a annual crops simple to cultivate and has low edafoclimatic requirements. These characteristics stirred up actual attempts to use cassava during the first stage of the Brazilian Ethanol Program (Proálcool), in the 1970s. Nonetheless, such projects were not successful, mainly because the high price of cassava bioethanol vis-à-vis sugarcane bioethanol and interruptions in the supply of roots to the industry. In recent years some Asian countries have been fostering bioethanol fuel production based on cassava [Howeler (2003)], with good results in Thai distillation plants [Koisumi (2008)].

In bioethanol production cassava roots are peeled off, washed and grounded to get a mix that in successive stages is put into kilns and tanks for starch saccharification, in processes similar to those used for corn bioethanol. With industrial productivity rates similar to those for corn, one ton of non-processed cassava with around 25% of starch allows producing 170 litres of bioethanol. On the agricultural side, average agricultural productivity in well-managed crops in Brazil yield around 18 tons per hectare [Mandioca Brasileira — Brazilian Cassava (2008)]; that is, 3,060 litres of bioethanol per hectare. Significant co-products have not been identified in cassava-based biethanol production, apart from vinasse from the distillation process [Trindade (1985)]. Sweet potato could be processed in a similar way as cassava for bioethanol production; however it has higher costs and results so far have been limited.

Wheat (*Triticum spp.*), another starch-producing crop, has been effectively applied in recent years to produce bioethanol in some European countries, such as England and Germany, by means of an industrial process rather similar to that used in corn bioethanol. Typical agricultural and industrial productivities are, respectively, of 7.5 tons per hectare and 240 litres of bioethanol per ton of processed grains [LowCVP (2004)], which yield 1,800 litres per hectare. In addition, around 320 kg of co-products are obtained per ton of processed wheat, which can be used for animal feeding — as in the case of corn . Barley and rye crops are also being adopted to produce bioethanol fuel in several European countries, but at a lower scale.

Sugar beet (*Beta vulgaris*) is another sugar crop — in addition to sugarcane — that is used to manufacture bioethanol, using residual honey (molasse) always available in saccharose industrial production [Tereos (2006)]. This vegetable has a tuberous root that accumulates high amounts of sugar, delivering outputs of 50 and 100 tons per hectare and saccharose contents around 18% [RIRDC (2007)]. It may reach rather high agroindustrial productivity levels, of around 7,500 litres of bioethanol per hectare, which is quite similar to sugarcane productivity levels. Industrial processing begins by cleaning and fractioning the beet in fine slices that are then sent to a diffuser, in which they are successively washed under hot water to induce sugar release. The liquid resulting from this operation contains around 16% of soluble solids extracted from the beet, which are then processed in similar way to sugarcane juice, into crystallized sugar or into bioethanol. One ton of tubers usually produces 86 litres of bioethanol and 51 kg of a fibrous cake that may be used as animal feed [El Sayed et al. (2005)]. In spite of presenting high productivity, beet depends on external power (electricity and fuel) to be processed.

Sweet sorghum (*Sorghum bicolor (L.) Moench*) is often pointed out as a potential bioethanol feedstock; however, there is no current significant bioethanol production based on it. Particularly, the use of sorghum to produce bioethanol may be even integrated to the sugarcane agroindustry, extending the usual crop season with a crop relatively simpler than sugarcane, with several similarities when it comes to processing. Sweet sorghum stems may be processed in mills, producing a sugary juice — with saccharose content lower than the one found in sugarcane juice — that may then be subject to a similar industrial process to produce molasses and bioethanol.

Sweet sorghum can deliver more than 2,000 litres of bioethanol per hectare, considering an industrial productivity of 40 litres of bioethanol per ton of processed sorghum [Icrisat (2004)] and an agricultural productivity of 50 tons per hectare. Such productivity has been observed in BR 505 sorghum croplands developed by Empresa Brasileira de Pesquisa Agropecuária (Brazilian Agricultural Research Company — Embrapa) at Centro Nacional de Pesquisa de Milho e Sorgo (Brazilian National Corn and Sorghum Research Center), aiming at producing bioethanol [Teixeira et al. (1997)]. Nonetheless, using sweet sorghum still poses difficulties that must be overcome before its effective adoption, especially regarding its weak resistance to degradation after harvest, limited germplasm base, low environmental friendliness and low resistance to pests and diseases [Venturi and Venturi (2003)]. Actually, sorghum experiments in the State of São Paulo mills did not achieve significant results, even when intercropped with sugarcane [Leal (2008)].

There are currently high expectation on fast-growing and high-yield grasses, especially in light of the development of innovative ethanol production routes in the near future, by means of hydrolysis of cellulosic materials (see Chapter 5). In addition to forestry species (such as eucalyptus) and some leguminous trees (particularly, *Leucaena spp*.), the new bioethanol routes based on cellulosic biomass will allow using grasses such as Elephant grass (*Pennisetum purpureum*), generally used as forage plant in Brazil, switchgrass (*Panicum virgatum*), native to North America, which could produce several annual cuts, as well as tallgrass genus *Miscanthus*, of high interest in Europe.

In choosing bioethanol feedstock crops it is crucial to consider overall efficiency requirements. Thus, among other aspects, it is worth prioritizing crops that minimize soil, water and external agrochemical addition requirements, as well as economic feasibility considerations. It is senseless to propose the use of sophisticated crops with good alternative market value as bioenergy sources. Feedstock represents typically 60% to 70% of bioethanol final cost; thus, pursuing low-cost feedstock alternatives is critical. Co-products and by-products of nutritional, industrial or energy value, are equally important to the extent that they may provide a desirable flexibility in bioenergy production, associating biofuels to other sources of economic value.

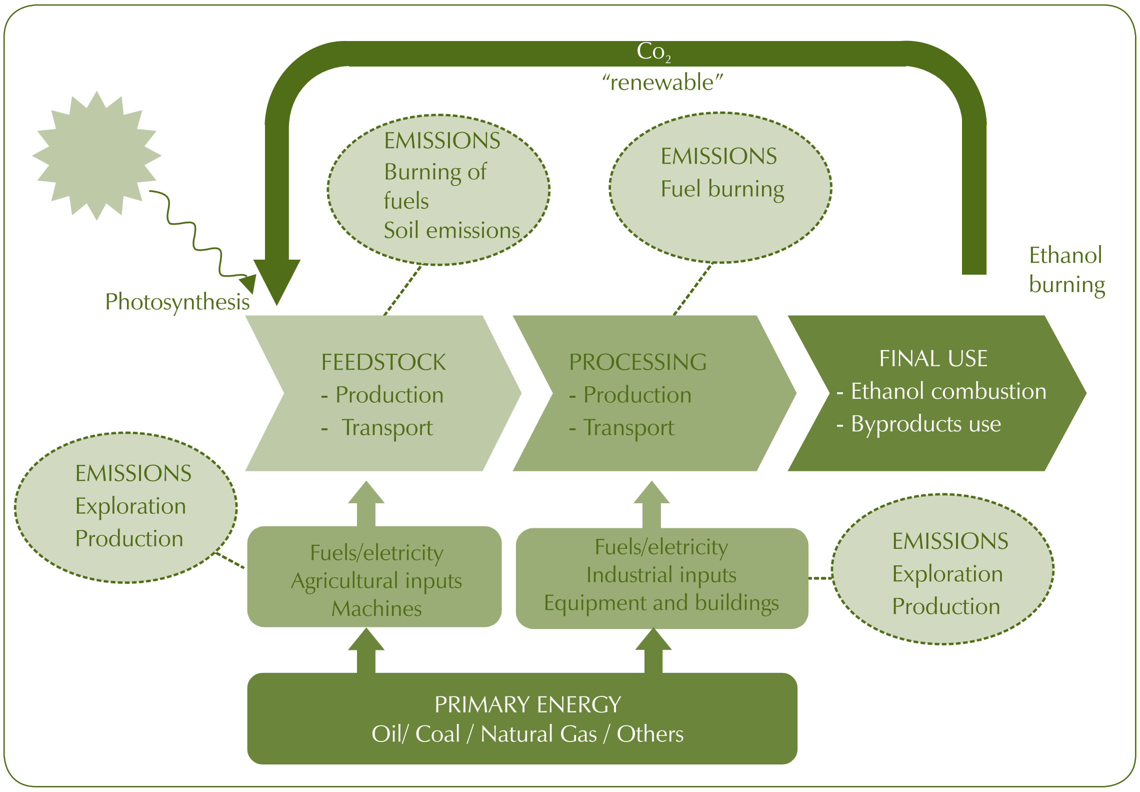
Another important issue for properly choosing biomasses with potential to produce bioethanol is the energy balance, ie, the relationship between the direct and indirect energy used to produce a bioethanol vis-à-vis the energy delivered by the biofuel produced. It is therefore desirable to use crops with high productivity and low demand of external energy inputs. This subject will be addressed in the next section.

The need of understanding clearly what is that makes a crop an innovative option for bioethanol production stresses the importance of more in-depth agronomic, economic and technology studies that allow more sound recommendations. As knowledge on such crops increases, diversification of the supply of feedstock to produce bioethanol will eventually take place, relying on stronger and more sustainable grounds. Production of such crops could eventually will become possible in environments where there is currently high interest, such as saline soils with low water requirements. Irrespective of the scenario, bioethanol production will not be deemed as substituting current agricultural production; however, it can become a new activity designed to use marginal lands, expanding and diversifying agricultural practices.

3.5 Productivity, emissions and energy balances

Notwithstanding the biomass used, the main purpose of bioethanol production is substituting oil derivatives, which allows diminishing the dependency on such fossil resources and reducing GHG emissions. However, the extent to which biofuel may replace a fossil fuel essentially depends on how it is produced. As all production technologies directly or indirectly involve the use of fossil resources, the benefit associated to the use of a biofuel depends on effectively saving the non-renewable energy it delivers when compared to its fossil equivalent. Proper calculation of the energies involved in the agroindustrial production process requires consideration to the lifecycle GHG emissions, from farm to final use, as shown in Figure 15.

***Figure 15* – Biofuel lifecycle diagram**



Source: Seabra (2008).

As seen in Figure 15, the boundaries of the system to be analyzed may change, depending on the study carried out; however, lifecycle analyses generally aim at determining energy consumption and GHG emissions from feedstock production through final fuel use. Energy consumption and emissions associated with the production of inputs and equipment used in the fuel production chain are also considered. It is worth noting that, in principle, all CO_2 released when burning biomass products in one period is recycled by means of photosynthesis during biomass growth in the next production cycle, but the share corresponding to fossil fuels consumed in bioethanol production means a net increase of these gases in the atmosphere.

Some questions on the impact of land-use changes have arisen recently, especially regarding GHG emissions. It is asserted that — depending on the previous vegetation in the area used for biofuel-related feedstock production — the disturbances caused by land-use changes could release to the atmosphere an amount of carbon previously "restrained" in vegetation and soil, high enough to jeopardize the positive environmental benefits of biofuel production. This issue is yet rather controversial, mainly because there is a lack of sufficient data on the effect to anticipate conclusions.

In any case, land-use related emission is a subject matter that deserves attention; further research is then necessary to consistently estimate the actual share of such emissions in the biofuels lifecycle. Nevertheless, at least in Brazil, forest cover losses and bioethanol production associations are least probable, as expansion of sugarcane production has taken place mainly in areas previously occupied by low productivity pastures or by annual crops usually designed for export, which generally have lower carbon retention than sugarcane-raising activities. Another aspect to considered is the effect of increasing green sugarcane harvest, with higher amount of straw and, therefore, of carbon incorporated to the soil.

Without examining in detail such issue, several studies were already carried out to assess energy and environmental impacts of biofuels. In the case of sugarcane bioethanol production in Brazil several environmental advantages are already known, especially considering the replacement of gasoline and GHG emissions reductions, since the disclosure of first detailed studies on the subject [Macedo and Horta Nogueira (1985) and Macedo (1992)]. Since then, updating studies have been published [Macedo (1998) and Macedo et al. (2004)], following up the development of agroindustrial practices and the improvement of knowledge on environmental aspects of the sugarcane industry in general.

The last assessment study published analyzes the energy and GHG emission balances for the current situation and for a 2020 scenario, considering an approach "from sugarcane crops to the mill gate" [Macedo et al. (2008)]. The study concludes that nowadays — based on the average rates of key agricultural and industrial parameters of 44 mills in the Center-South Region of Brazil — for each fossil energy unit used to produce sugarcane bioethanol, more than nine renewable energy units are produced, in the form of bioethanol and surpluses of electric power and bagasse, as shown in Table 12. Moreover, the ratio of energy production to energy consumption is expected to increase above 11 by 2020, even in a scenario of higher mechanization and use of agricultural technologies that increase the energy demand by 12%, mainly because of the increase in bioethanol production per unit of processed sugarcane and the significant increase of electric power production. The estimates assume electric power surpluses of 9.2 kWh and 135 kWh per ton of sugarcane in 2005/2006 and 2020, respectively; and thermal rates in cogeneration systems of 9 MJ/kWh and 7.2 MJ/kWh, in the same periods. These values are consistent with technologies available and those under development, which in the case of cogeneration consider the use of sugarcane straw (40% of recovery) as a supplemental fuel to bagasse in systems with high pressure extraction-condensation turbines and processes with reduced consumption of steam (340 kg of steam per ton of processed sugarcane) [Macedo et al. (2008)].

Regarding GHG, current production of sugarcane anhydrous bioethanol involves emissions of almost 440 kg CO_2eq/m^3 of bioethanol, with prospective reduction in the years to come, as shown in Table 13. In addition, bioethanol use in 25% gasoline blends — as adopted in Brazil — results in a net GHG emission reductions of around 1,900 kg CO_2eq/m^3 of bioethanol, in current conditions, and it will possibly reach levels above 2,260 kg CO_2eq/m^3 of bioethanol by 2020, as shown in Table 14. The net increase in emissions reduction will be associated to the use of bagasse and electricity surpluses and net emissions avoided (resulting from the difference between emissions in production and emissions avoided). This is because, when gasoline is replaced by bioethanol all emissions associated to the use gasoline are mitigated, and only emissions related to bioethanol production are then taken into account. The calculations also assume that surplus bagasse must replace fuel oil in boilers and that electric power produced in the bioethanol agroindustry becomes the electric power generated, using world average emission factors (579 and 560 t CO_2eq/GWh for 2005 and 2020, respectively) [Macedo et al. (2008)].

***Table 12* — Energy balance of sugarcane bioethanol production in Brazil (MJ/tc)**

Energy balance component	**2005/2006**	**2020 Scenario**
Sugarcane production and transport	210.2	238.0
Bioethanol Production	23.6	24.0
Fossil Input (total)	233.8	262.0
Bioethanol	1,926.0	2,060.0
Bagasse surplus	176.0	0.0
Electricity surplus	82.8	972.0
Renewable *Output* (total)	2,185.0	3,032.0
Energy production/consumption		
Bioethanol + bagasse	9.0	7.9
Bioethanol + bagasse + electricity	9.3	11.6

Source: Macedo et al. (2008).

***Table 13* – Emissions from sugarcane bioethanol production in Brazil (kg CO_2eq/m^3)**

	2005/2006		2020 Scenario	
Bioethanol				
Total emission	417	436	330	345
Fossil fuels	201	210	210	219
Vegetation Fires	80	84	0	0
Soil	136	143	120	126

Source: Macedo et al. (2008).

***Table 14* – Net emissions from sugarcane bioethanol production and use in Brazil (kg CO_2eq/m^3)**

	2005/2006		2020 Scenario		
Form of bioethanol use	E100	E25	E100	E100-FFV*	E25
Avoided Emissions	2,181	2,323	2,763	2,589	2,930
Use of surplus biomass	143	150	0	0	0
Electricity surplus	59	62	784	784	819
Use of bioethanol	1,979	2,111	1,979	1,805	2,111
Net emissions	-1,764	-1,886	-2,433	-2,259	-2,585

Source: Macedo et al. (2008).
* FFV: flex fuel vehicles

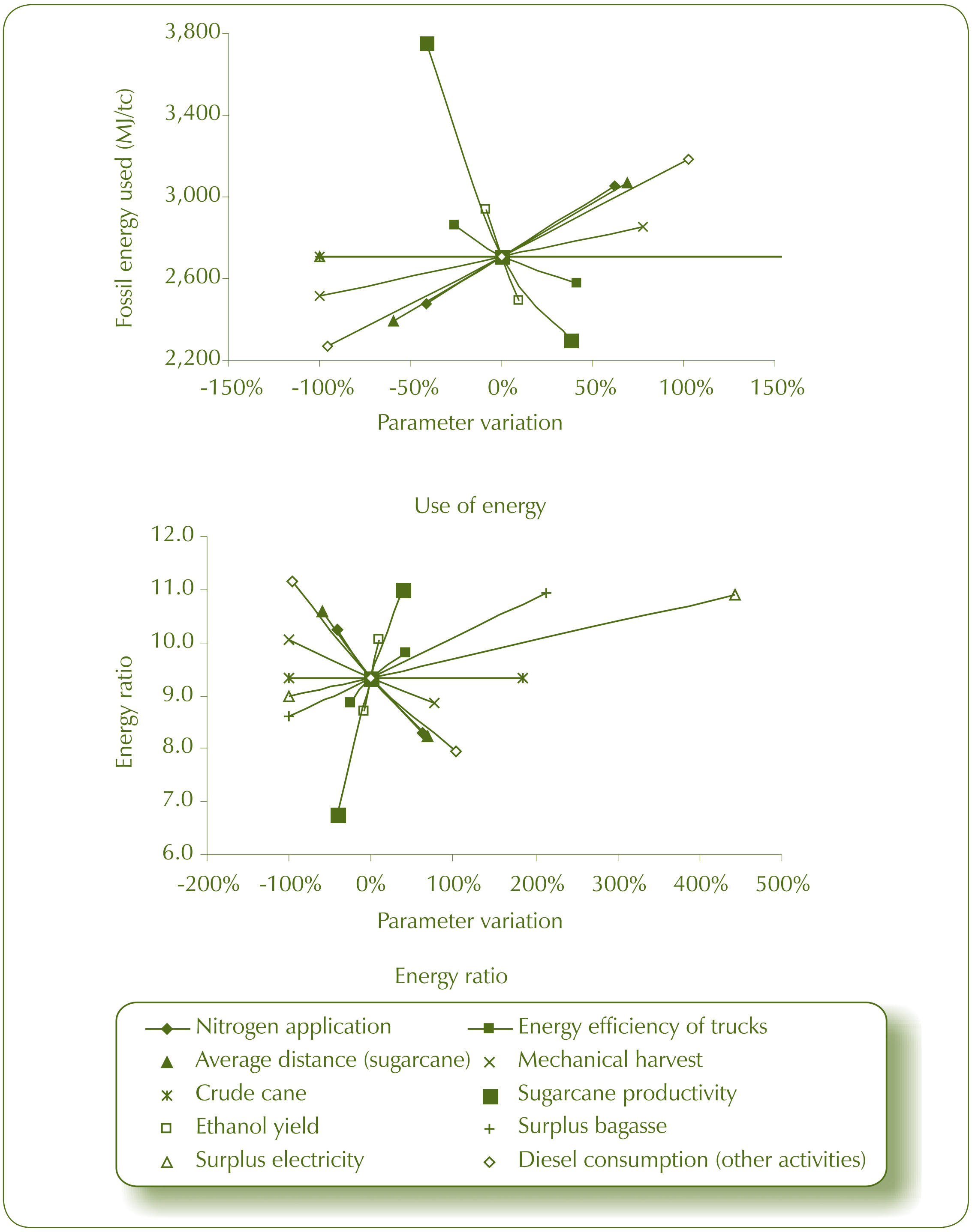
It is also important to keep in mind that these results are based on sample average conditions of Brazilian Center-South mills, which may present varying energy balances as agricultural and industrial parameters of each mill are considered. Figure 16 illustrates the individual influence of these varying parameters on energy use in mills and on the energy production to energy consumption ratio. Figure 17 presents the sensitivity of GHG gross and net emissions, considering the change intervals for these mills. Within such limits, the results may be considered typical for the energy agroindustry based on sugarcane with good performance indicators, such as practiced in several tropical countries with proper climate for the crop.

Bioethanol production based on sugarcane is already a developed technology, and there is not much room for major increases in productivity, particularly at the industrial stage. However, perspectives are different for bioethanol production based on sugarcane lignocellulosic materials, such as bagasse and straw. Current trends show that mills are very likely to turn into producing units, not only of sugar and bioethanol, but also of significant amounts of electricity, an energy of higher quality and economic value than fuels, per unit of energy produced. Advanced new cogeneration options, combined with lower energy demand processes are steps in that direction. In the near future a significant part of the straw will be added to bagasse as supplemental fuel, producing electric power at levels even higher than electric power surpluses, higher than 100 kWh per ton of processed sugarcane. Bearing this in mind, it is reasonable to expect that by 2020 the ratio between production of renewable energy and consumption of fossil energy in sugarcane bioethanol will be close to 12, with net emissions avoided around 2,600 kg CO_2eq/m^3 of bioethanol [Macedo et al. (2008)].

There is also controversy on the environmental benefits of using corn bioethanol to replace gasoline. In any case, there is no doubt that, even in the best scenario, the benefit is far below that of sugarcane bioethanol. This is because although processing corn into bioethanol demands significantly lower amounts of energy than sugarcane to be converted into bioethanol, in corn processing all energy comes from external fossil sources. The steam required (10.6 MJ/litre) is produced in natural gas boilers, and electricity (0.4 kWh/litre) is supplied by the public grid, which in the US depends on fossil-fuel sources to a large extent [Pimentel and Patzek (2005)].

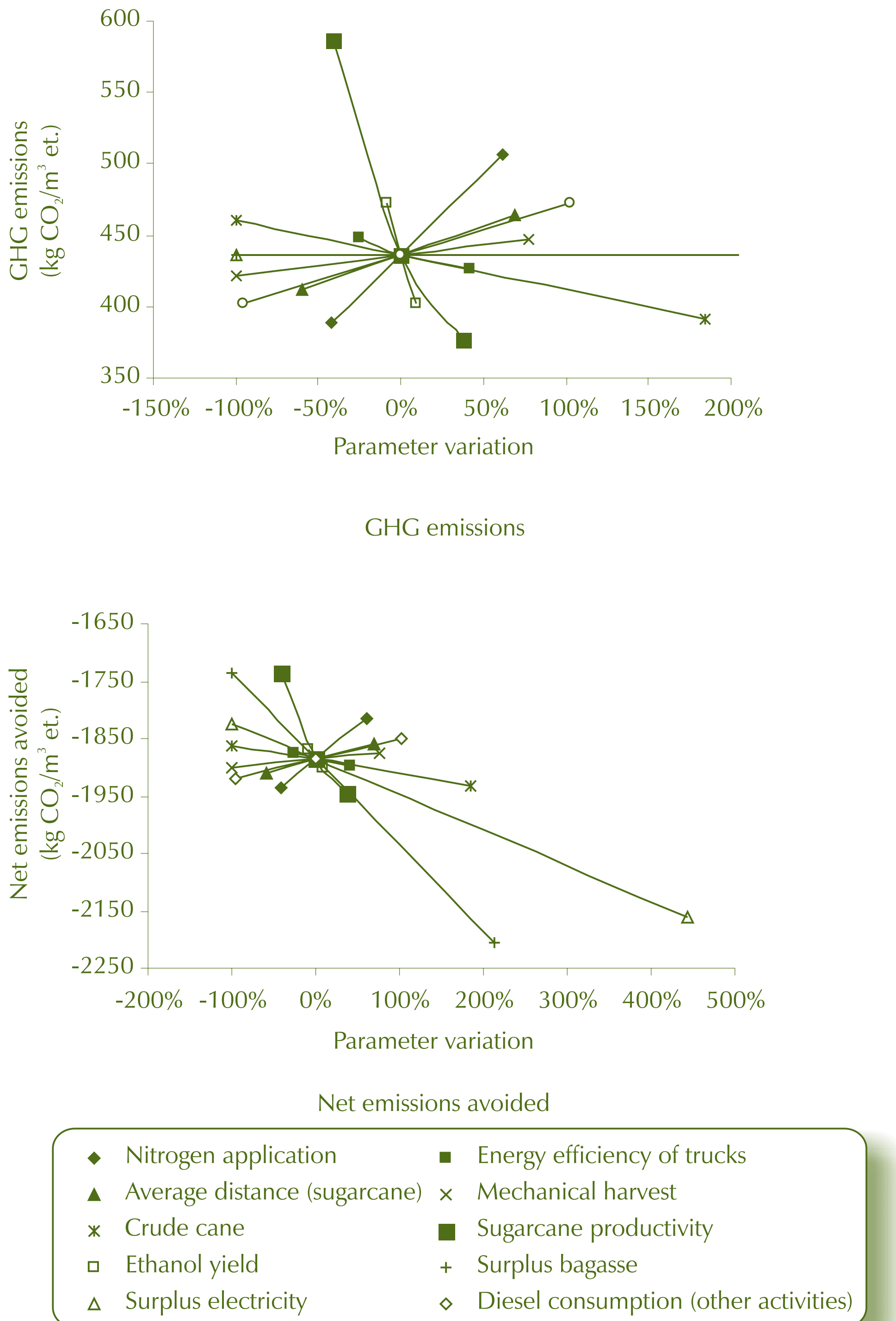
A recent comparative study that analyzed several studies [EBAMM (2005)] concludes that the most representative energy ratio for corn bioethanol in the US is 1.3, considering co-product credits, such as DDGS. As for emissions, corn bioethanol production involves total emissions of around 1.700 kg $CO_2 eq/m^3$ of bioethanol (also considering co-product credits), with avoided net emissions of 130 kg CO_2eq/m^3 of bioethanol, considering its final use, as shown in Table 15. Note that this value is almost 15 times lower than the value observed in sugarcane bioethanol.

Figure 16 **– Analysis of sensitivity for sugarcane bioethanol in 2005/2006: use of energy and energy ratio**



Source: Macedo et al. (2008).

Figure 17 – **Analysis of sensitivity for sugarcane bioethanol in 2005/2006: GHG emissions and GHG net avoided emissions**



Source: Macedo et al. (2008).

***Table 15* – Energy and GHG emission balances for corn bioethanol in the USA**

Energy flows	Value
Consumption at agricultural stage	5.59 MJ/litre
Consumption at industrial stage	15.24 MJ/litre
Total consumption	20.83 MJ/litre
Bioethanol production	21.20 MJ/litre
Co-products energy value	4.13 MJ/litre
Total *output*	25.33 MJ/litre
Energy ratio (production/consumption)	1.2
Balance of emissions	
Agricultural stage	868 kg CO_2eq/m^3
Industrial stage	1,353 kg CO_2eq/m^3
Co-products	-525 kg CO_2eq/m^3
Emission in bioethanol production	1,696 kg CO_2eq/m^3
Bioethanol emissions	81 g CO_2eq/MJ
Gasoline emissions	94 g CO_2eq/MJ
Net emissions	134 kg CO_2eq/m^3

Source: Farrell et al. (2006) and EBAMM (2005).

Just like sugarcane bioethanol, corn bioethanol production is also a developed technology. Then, we must expect the next improvements in the pursuit of a better environmental performance to come from using the remaining biomass (straw) as fuel or input to increase bioethanol production, possibly by means of hydrolysis. However, the use of this biomass is quite limited, given the significant role it plays in soil quality preservation.

The situation is not that different for other bioethanol feedstocks, at least for beet, wheat and cassava, as shown in Table 16; that is, the energy ratio and avoided emissions values are rather low [Dai et al. (2006), EBAMM (2005), IEA (2004), Macedo et al. (2007) and Nguyen et al. (2007)].

***Table 16* – Comparison of different feedstock for bioethanol production**

Feedstock	Energy ratio	Avoided emissions
Sugarcane	9.3	89%
Corn	0.6 – 2.0	-30% a 38%
Wheat	0.97 – 1.11	19% a 47%
Beet	1.2 – 1.8	35% a 56%
Cassava	1.6 – 1.7	63%
Lignocellulosic residues*	8.3 – 8.4	66% a 73%

Source: Produced based on Dai et al. (2006), EBAMM (2005), IEA (2004), Macedo et al. (2007) and Nguyen et al. (2007).
*Theoretical estimate, process under development

Therefore, with the exception of sugarcane bioethanol, the energy and GHG emission balances of most bioethanol feedstock are not encouraging. That is why expectations for improvement lay in the production of biofuel based on lignocellulosic materials, taking into account both environmental criteria and production potential. Nonetheless, cellolosic ethanol is not yet a commercial technology and many research efforts and evidences are still needed for this option to be effectively feasible in the future. This subject will be addressed in Chapter 5.

Thus, the reduction of GHG emissions is possibly one of the most important positive effects associated with sugarcane bioethanol. According to the Brazilian First Communication to the United Nations Framework Convention on Climate Change, the use of sugarcane energy reduced by 13% the carbon emissions of the whole energy sector, based on values for 1994. Bioethanol replacement of gasoline and energy production from bagasse reduced CO_2 equivalent emissions by 27.5 million and 5.7 million tons, respectively, in 2003. [Goldemberg et al. (2008)]. Moreover, for every 100 million tons of sugarcane used in energy production purposes, emissions of 12.6 million tons of CO_2 equivalent could be avoided, considering bioethanol, bagasse and surplus of electric power supplied to the grid [Unica (2007)].